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DETERMINING THE TENSION OF COMPLEX CHEMICAL THREADS DURING INTERACTION WITH GUIDE SURFACES

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This paper reports a study to determine the tension of complex chemical threads made of Kevlar, carbon, polyethylene, and meta-aramid when interacting with the working bodies of knitting machines in the process of forming technical knitwear. An increase in tension after the guide surface of the working body due to a change in the value of the friction forces in the contact zone was established. It has been proven that the tension of the selected complex chemical threads after the guide surface of the working body is affected by the tension of the thread in front of the guide surface of the working body of the knitting machine. Also, the amount of tension is affected by the radius of curvature of the cylindrical guide surface of the working body and the angle of thread coverage of the guide surface of the working body of the knitting machine. This has made it possible to determine thread tension even at the initial stage of designing the technological process of thread processing on knitting machines, during the production of technical knitwear. On the basis of experimental studies for Kevlar, carbon, polyethylene, and meta-aramid complex threads, regression dependences of the stress after the cylindrical guide surface of the working body of the knitting machine were constructed. The analysis of regression dependences made it possible to establish the value of the radius of curvature of the guides when the tension of complex chemical threads before the knitting zone on knitting machines would take a minimum value. This will minimize the stress on complex threads during their processing.

So, there are reasons to assert the possibility of directed regulation of the process of changing the tension of Kevlar, carbon, polyethylene, and meta-aramid complex threads during the formation of technical knitwear on knitting machines by selecting the value of the geometric parameters of the guides

Keywords: thread tension, chemical thread, guide surface, surface curvature, angle of coverage

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1. Introduction

Chemical threads, namely Kevlar, carbon, polyethylene, and meta-aramid complex threads are widely used in the production of technical knitted fabrics. This is explained by their specific physical and mechanical properties.

When producing technical knitted fabrics, the tension of chemical threads on flat knitting and circular knitting machines is a determining factor for assessing the tension of the knitting process. The improvement of technological processes is connected with the optimization of the tension of chemical complex threads in front of the zone of formation of technical knitwear. Experimental determination of tension in front of this zone causes great difficulties. This does not make it possible to determine the amount of tension even at the initial stage of designing the technological process of obtaining technical knitwear from Kevlar, carbon, polyethylene, and meta-aramid threads. As a result, it is not possible to improve the shape of the thread filling line on flat knitting and circular knitting machines, select the design parameters of the guide elements at the points of the filling line break. Under these conditions, the study of the process of increasing the tension of the thread in the zones of flat knitting and circular knitting machines can provide essential help. The sequential determination of the tension of the chemical threads along the filling zones between the guide elements makes it possible to obtain the dependence of the change in the tension of the chemical threads on the point of departure from the bobbin to the knitting zone.

An increase in the tension of the chemical threads in front of the forming zone leads to its breaking, which entails a stoppage of the machine, in which there are hundreds of threads.

The increase in the tension of chemical threads occurs due to the frictional forces in the contact zone with the guide and working bodies of flat and circular knitting machines. The magnitude of the friction forces depends on the material of the chemical threads and the guide, the ratio of their geometric dimensions (the radius of the cross section of the chemical threads and the radius of curvature of the guide in the contact zone). Also, the force of friction depends on the actual angle of coverage of the guide by the chemical threads, the physical-mechanical and structural characteristics of the chemical threads, the tension of the thread in front of the guide. The successive passage of the thread along the guiding and working bodies, from the entrance zone to the zone of formation of technical knitwear, leads to a gradual increase in tension. At the same time, the output parameter of the tension after the previous guide will be the input parameter for the next guide.

In this regard, research into determining the tension of complex chemical threads when interacting with the guiding surfaces of the working bodies of flat knitting and circular knitting machines should be considered relevant.

2. Literature review and problem statement

In work [1], the values of the tension of the threads before the zone of fabric and knitwear formation on the technological equipment are determined. It is shown that the amount of thread tension in front of the formation zone is influenced by the number of guides on each specific technological machine, the radius of curvature of each guide, the angle of coverage by the thread of the guide, the angle of radial coverage of the thread. But the questions related to the determination of the tension of chemical complex threads with guiding surfaces, the radius of curvature of which is commensurate with the calculated radius of chemical threads, remained unresolved.

The results of determining thread tension on knitting machines with a feeder guide are given in [2]. When determining the tension, the real conditions of interaction in the contact zone, taking into account the bending stiffness and deformation of the thread in the contact zone with the large curvature guide, are not taken into account. The results of the work cannot be used to determine the tension of chemical threads when they interact with guides of great curvature. The influence of the radius of curvature of the guides and working bodies on the tension of the processed raw material is considered in [3]. But the questions related to the determination of the tension of chemical complex threads with guiding surfaces, when the radius of curvature is commensurate with the calculated radius of chemical threads, remained unresolved. The influence of physical and mechanical characteristics of processed raw materials on technological efforts on technological equipment is considered in paper [4]. However, the results of the work cannot be used to determine the tension of chemical threads when they interact with guides of great curvature.

Studies on determining the tension of cotton yarn are given in [5]. When determining the tension of cotton yarn, the case when the guiding surfaces have a small curvature is considered. Thus, the obtained results cannot be used when determining technological efforts on flat and round knitting machines of chemical complex threads when interacting with guides of great curvature.

Work [6] considers the experimental determination of thread tension when interacting with guiding surfaces. However, the range of changes in the input tension and the radii of curvature of the guiding surfaces do not correspond to the real conditions of processing chemical complex threads in the production of technical knitwear. Complex experimental studies of the interaction of threads with guides are reported in [7]. The obtained regression dependences of the tension of complex threads on the structural parameters of filling cannot be used for chemical threads that have specific physical and mechanical properties. Paper [8] describes the experimental setup for determining thread tension. Its disadvantage is the impossibility of changing the amount of variable factors that affect the tension of the thread after the guide. Analogous approaches for determining technological efforts in the processing of complex threads are given in [9]. In work [10], the tension of complex threads is determined using a rotating cylinder of small curvature. This scheme of the experimental setup does not allow determining the tension of the chemical threads for the case of a guide surface of great curvature. The account of the direction of relative sliding of rubbing surfaces is given in [11]. In the case of determining the tension of chemical complex threads on flat knitting and circular knitting machines, the relative displacement of chemical complex threads and guides can be neglected.

The interaction of complex threads with guiding surfaces in the form of a torus is given in [12]. The obtained regression dependences of the tension of complex threads on the structural parameters of filling cannot be used for chemical threads that have specific physical and mechanical properties. The consideration of the bending stiffness of the thread when determining its tension is presented in [13]. For complex threads and yarns, this factor can be taken into account if the twist of the threads approaches the critical one. Work [14] reports the results of determining the tension of complex threads with a rotating guide cylinder. This type of thread interaction with the guide is absent in the thread feeding system on flat knitting and circular knitting machines.

It is necessary to take into account the torsion of complex threads by the value of their bending stiffness [15]. Bending stiffness significantly affects the value of the actual angle of coverage of the guide surface by the thread. When the twist of the threads increases, their bending stiffness increases, which leads to a decrease in the angle of coverage [16]. In the proposed study, the twist of Kevlar, carbon, polyethylene, and meta-aramid complex threads was 100 twists per meter, which made it possible to neglect bending stiffness.

The design of the experimental setup determines the accuracy of the obtained results when determining the tension of the chemical thread. There is a scheme for determining thread tension, in which cylinders of large radii are used as guides [17]. Such a scheme does not allow modeling the real conditions of interaction of the chemical thread with the guiding and working bodies of flat knitting and circular knitting machines. The experimental installation with a rotating cylinder also has such disadvantages.

The study of the processes of interaction of threads and fabrics with guiding surfaces makes it possible to obtain analytical dependences of the relative movement of materials [18]. The obtained dependences make it possible to analyze the mechanical behavior of materials [19]. Modeling the process of processing and transporting materials along guides allows predicting changes in their properties [20]. Changing the structure of materials in the contact zone with the guide will affect their thermal properties and permeability [21].

Thus, our review of the theoretical and experimental work on determining the tension of threads in interaction with guide surfaces allowed us to establish that the obtained results cannot be used to determine the law of tension change in the filling zones of chemical threads on circular knitting and flat knitting machines in the production of technical knitted fabrics, which are used in the manufacture of power grabs for laying pipes with factory insulating coating, bulletproof vests, protective elements (reinforcement of soles, sidewalls), military shoes (shins) for protection against anti-personnel mines. This is explained by the fact that in the considered experiments, the selection of the radius of curvature of the guides, the angle of coverage by the guide thread and the tension in front of the guide differ from the real values that occur on circular knitting and flat knitting machines when processing chemical threads. The guiding and working bodies of circular knitting and flat knitting machines have a radius of curvature of the guiding surface, which varies within the limits: from 0.8 to 2.2 mm for needles, plates, cylindrical guides, and control elements of thread breakage control devices; from 5 to 15 mm for the working bodies of the thread tensioner, tension compensators, thread feeder conveyors. The value of the real coverage angle varies from 72° to 130°.

The tension must be determined taking into account the material of the chemical threads and the guide and the ratio of their geometric dimensions (the radius of the cross section of the chemical threads and the radius of curvature of the guide in the contact zone). It is also necessary to take into account the actual angle covered by chemical threads of the guide, the physical-mechanical and structural characteristics of the chemical threads and the tension of the thread in front of the guide.

3. The aim and objectives of the study

The purpose of this study is to determine the optimal value of the radius of curvature, at which the tension of the chemical threads when interacting with the guiding surfaces of large curvature would take a minimal value. This will make it possible to minimize the tension of chemical complex threads on flat knitting and circular knitting machines in the production of technical knitwear.

To achieve the set goal, the following tasks must be solved:

– for chemical threads, obtain regression dependences of the influence of the radius of curvature of the guide, which varies from 0.8 to 2.2 mm, the real angle of coverage by the guide thread, the tension of the chemical threads before the guide on the amount of tension after the guide surface;

– for chemical threads, obtain regression dependences of the influence of the radius of curvature of the guide, which varies from 5 to 15 mm, the real angle of coverage by the guide thread, the tension of the chemical threads before the guide on the amount of tension after the guide surface.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the technological process of processing chemical threads on flat knitting and circular knitting machines.

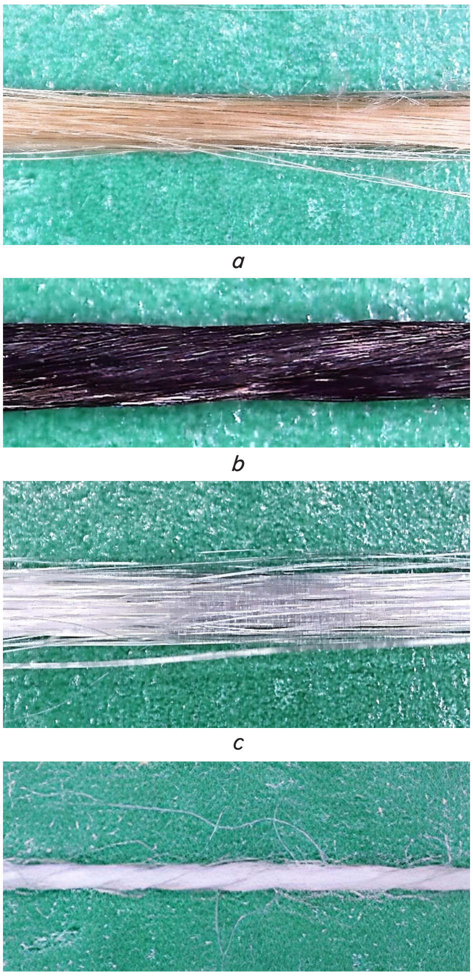
The subject of the study is the tension of chemical threads after the guide and working bodies of large curvature of flat knitting and circular knitting machines.

The research hypothesis assumes the influence of the curvature of the guide and working bodies of flat knitting and circular knitting machines on the amount of tension of chemical threads.

4. 2. Selected materials

In the production of technical knitted fabrics, chemical complex threads were selected: Kevlar complex thread KE (68 Tex, 1100 filaments, 210 cN/Tex) of increased strength, Fig. 1, *a*, and carbon complex SA thread (H-70, 70 Tex, 2000 filaments, 25 cN/Tex), Fig. 1, *b*. Polyethylene complex RO thread (88 Tex, 240 filaments; 103 cN/Tex) was also used for the experiment, Fig. 1, *c*, and meta-aramid heat-resistant complex thread MA (80 Tex, 600 filaments; 32 cN/Tex), Fig. 1, *d*. Chemical complex threads were selected of approximately the same thickness.

Sigeta USB digital microscope expert (magnification 10x–300x) was used to determine the transverse dimensions of the selected chemical threads.



a

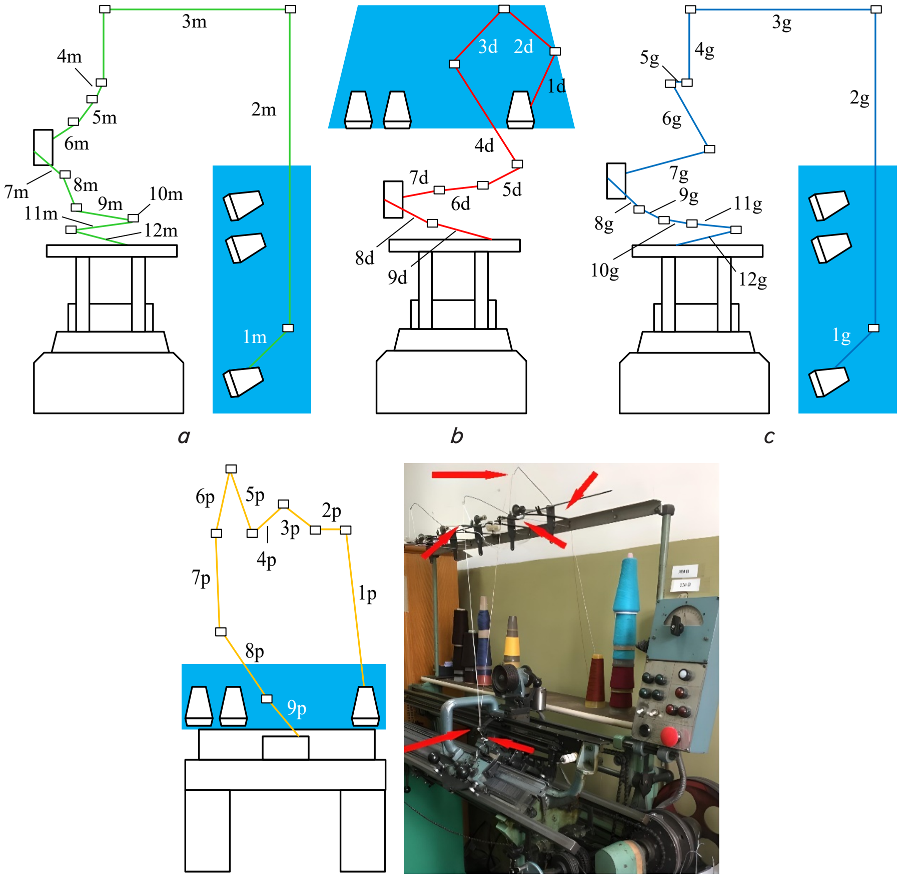
b

c

d

Fig. 1. Threads for the experiment:
a – Kevlar complex thread 68 Tex; *b* – carbon complex thread H-70 with a thickness of 70 Tex; *c* – polyethylene complex thread 88 Tex; *d* – meta-aramid complex thread 80 Tex

Circular knitting and flat knitting machines are used for the production of technical knitted fabrics. Fig. 2 shows schemes of thread filling on knitting machines.



a b c

d e

Fig. 2. Thread filling schemes on knitting machines: *a* — circular knitting machine Mayer; *b* — circular knitting machine DL; *c* — Pailung circular knitting machine; *d* — flat knitting machine; *e* — a general view of a flat knitting machine

Fig. 2, *a* shows the thread filling scheme on the Mayer circular knitting machine. Fig. 2, *b* shows the thread filling scheme on the DL circular knitting machine. Fig. 2, *c* shows the thread filling scheme on the Pailung circular knitting machine. Fig. 2, *d* shows the thread filling scheme on a flat knitting machine. Fig. 2, *e* shows the general view of the flat knitting machine.

The thread feeding system of the Mayer circular knitting machine consists of 12 zones. In the zone 1m – 2m, the thread comes off the bobbin and enters the feeder through its hole. In this case, the thread interacts with the guiding surface of the hole in the form of a torus. When determining the tension at the end of the zone 1m – 2m, it is necessary to take into account the change in the coefficient of friction depending on the curvature of the guide, the stiffness of the thread upon bending, the deformation of the thread in the zone of contact with the guide. The real value of the angle of coverage of the guide thread should be determined taking into account these factors. In the zone of 2m – 3m, the thread wraps around a rectangular feeder elbow. Taking into account the real geometric dimensions of this structural element, it is possible not to take into account the radial coverage. In the 3m – 4m zone, the thread wraps around the second rectangular feeder elbow. In zones 7m – 8m and 8m – 9m, the thread interacts with guides in the form of a torus. In zones 9m – 10m and 10m – 11m, threads interact with the thread break controller. In the zone 11m – 12m, the thread interacts with the guiding element of the thread.

The thread filling line on the DL-4M circular knitting machine consists of 12 zones. In zone 1d – 2d, the thread leaves the bobbin and enters the guide element of the DL-4M circular knitting machine. In zone 2d – 3d, the thread interacts with the guides of the first thread break controller. In zone 3d – 4d, the thread interacts with the second guide of the DL-4M circular knitting machine. In zone 4d – 5d, the thread interacts with the third guide of the DL-4M circular knitting machine. In zone 5d – 6d, the thread interacts with the finger device for thread tension. In zone 6d – 7d, the thread interacts with the guides of the second controller of thread breakage. In zone 7d – 8d, the thread interacts with the drum-type thread vertical accumulator. In zone 8d – 9d, the thread interacts with the guides of the third controller of thread breakage. In zone 9d – 10d, the thread interacts with the guiding element of the thread.

The thread filling line on the Pailung circular knitting machine can be conditionally divided into 12 zones. In the zone 1g – 2g, the thread leaves the bobbin and enters the guide element of the Pailung circular knitting machine. In the zone 2g – 3g, the thread interacts with the first rectangular elbow of the feeder.

In the zone 3g – 4g, the thread interacts with the second rectangular knee of the feeder of the Pailung circular knitting machine. In the 4g – 5g zone, the thread interacts with the first guide of the Pailung circular knitting machine. In the 5g – 6g zone, the thread interacts with the washer device for thread tension. In the zone 6g – 7g, the thread interacts with the second guide of the Pailung circular knitting machine. In the 7g – 8g zone, the thread interacts with the drum-type thread storage of the Pailung circular knitting machine. In the zone 8g – 9g, the thread interacts with the third guide. In the 9g – 10g zone, the thread interacts with the fourth guide of the Pailung circular knitting machine. In the zone 10g – 11g, the thread interacts with the thread break controller. In the zone 11g – 12g, the thread interacts with the guiding element of the thread.The thread filling line on a flat knitting machine can be conditionally divided into 9 zones. In zone 1p – 2p, the thread comes off the bobbin and enters the first guide element in the form of a torus in the flat knitting machine. In zone 2p – 3p, the thread interacts with the second guiding element in the form of a torus. In zone 3p – 4p, the thread interacts with the puck device for tensioning the flat knitting machine. In zone 4p – 5p, the thread interacts with the third guide element in the form of a torus in the flat knitting machine. In the zone 5p – 6p, the thread interacts with the tension compensator with a spring. In zone 6p – 7p, the thread interacts with the fourth guide element in the form of a torus in the flat knitting machine. In zone 7p – 8p, the thread interacts with the fifth guide element in the form of a torus in the flat knitting machine. In zone 8p – 9p, the thread interacts with the thread guide element in the flat knitting machine.

4. 3. Research methods

In the work, a second-order orthogonal plan for three factors is planned and implemented [4, 5, 7–12]. This plan was used for each of the variants KE, CA, PO, and MA to determine the combined influence of the tension of the driven branch of the warp thread P_0. Also, this plan was used to determine the radius of the cylindrical guide R and the calculated value of the angle of coverage φ_P for thread tension P after the guide element of the knitting machine. The general form of the regression equation takes the form:

$$P = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + \\ + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2. \qquad (1)$$

The range of variation of the factors in equation (1) was determined by the real conditions of processing Kevlar, carbon, polyethylene, and meta-aramid complex threads on circular knitting and flat knitting machines. Table 1 gives the range of variation of the radius of curvature of the guiding surface depending on the location zone in the thread filling on knitting machines. As a result of the implementation of the experimental plans, 10 parallel measurements were carried out for each of the KE, CA, PO, and MA variants and for each range of changes in the radius of curvature of the guide I and II.

Table 1

The range of variation of the radius of curvature of the guiding surface depending on the location zone in the thread filling on knitting machines

Location area in thread filling on knitting machines Fig. 3, *a–d*	Range of change in the radius of curvature of the guide surface, mm
1m – 2m, 7m – 8m, 8m – 9m, 9m – 10m, 10m – 11m, 11m – 12m, 1d – 2d, 2d – 3d, 3d – 4d, 4d – 5d, 6d – 7d, 8d – 9d, 9d – 10d, 1g – 2g, 4g – 5g, 6g – 7g, 8g – 9g, 9g – 10g, 10g – 11g, 11g – 12g, 1p – 2p, 2p – 3p, 4p – 5p, 5p – 6p, 6p – 7p, 7p – 8p, 8p – 9p	The range of change in the radius of curvature of the guide I 0.8–2.2
2m – 3m, 3m – 4m, 6m – 7m, 5d – 6d, 7d – 8d, 2g – 3g, 3g – 4g, 5g – 6g, 7g – 8g, 3p – 4p	The range of change in the radius of curvature of the guide II 5–15

Fig. 3 shows the diagram of the interaction of the thread with the cylindrical guide: *a* – Kevlar complex thread 68 Tex; *b* – carbon complex thread H-70 with a thickness of 70 Tex; *c* – polyethylene complex thread 88 Tex; *d* – meta-aramid complex thread 80 Tex.

Factor x_1 – the value of the filling tension for the range of changes in the radius of curvature of the guide I. In the center of the experiment for chemical threads: variant KE – for Kevlar complex thread 68 Tex – P_{0I}=32 cN; option CA – carbon thread H-70 with a thickness of 70 Tex – P_{0I}=26 cN; variant PO – polyethylene complex thread 88 Tex – P_{0I}=18 cN; variant MA – meta-aramid complex thread 80 Tex – P_{0I}=26 cN.

Factor x_2 – the radius of curvature of the guide for range I (Table 1) ranges from R_I=0.8 mm to R_I=2.2 mm. For range II, the radius of curvature of the guide ranges from R_{II}=5 mm to R_{II}=15 mm.

Factor x_3 – the calculated value of the angle of coverage of the guide for range I ranges from φ_{IP}=137° to φ_{IP}=173°. For range II, it fluctuates between φ_{IIP}=72° and φ_{IIP}=108°.

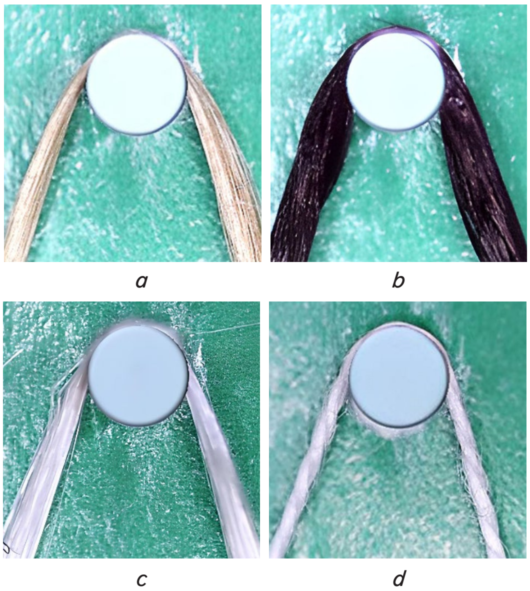


Fig. 3. Interaction of the thread with the cylindrical guide: *a* — Kevlar complex thread 68 Tex; *b* — carbon complex thread H-70 with a thickness of 70 Tex; *c* — polyethylene complex thread 88 Tex; *d* — meta-aramid complex thread 80 Tex

At the first stage, we determine the tension for the range of changes in the radius of curvature of guide I. Table 2 gives the second-order orthogonal plan matrix for four options KE, CA, PO, and MA.

Table 2

Matrix of the second-order orthogonal plan for four options KE, CA, PO, and MA for the range of changes in the radius of curvature of guide I

No.	Factor								
	Starting tension					Radius of curvature		Hugo coverage	
	x_1	P_{0I}, cN				x_2	R_I, mm	x_3	φ_{IP}, degree
		KE	CA	PO	MA				
1	+1	40	34	22	35	+1	2.1	+1	170
2	–1	24	18	14	17	+1	2.1	+1	170
3	+1	40	34	22	35	–1	0.9	+1	170
4	–1	24	18	14	17	–1	0.9	+1	170
5	+1	40	34	22	35	+1	2.1	–1	140
6	–1	24	18	14	17	+1	2.1	–1	140
7	+1	40	34	22	35	–1	0.9	–1	140
8	–1	24	18	14	17	–1	0.9	–1	140
9	–1.215	22	16	13	15	0	1.5	0	155
10	+1.215	42	36	23	37	0	1.5	0	155
11	0	32	26	18	26	–1.215	0.8	0	155
12	0	32	26	18	26	+1.215	2.2	0	155
13	0	32	26	18	26	0	1.5	–1.215	137
14	0	32	26	18	26	0	1.5	+1.215	173
15	0	32	26	18	26	0	1.5	0	155

The relationship between the named and coded values for the range of changes in the radius of curvature of guide I for chemical complex threads is as follows:

– variant KE – Kevlar complex thread 68 Tex:

$$x_1 = \frac{P_{0I} - 32}{8},\ x_2 = \frac{R_I - 1.5}{0.6}, x_3 = \frac{\varphi_{IP} - 155}{15}; \tag{2}$$

– variant CA – H-70 carbon filament with a thickness of 70 Tex:

$$x_1 = \frac{P_{0I} - 26}{8}, x_2 = \frac{R_I - 1.5}{0.6},\ x_3 = \frac{\varphi_{IP} - 155}{15}; \tag{3}$$

– variant PO – polyethylene complex yarn 88 Tex:

$$x_1 = \frac{P_{0I} - 18}{4}, x_2 = \frac{R_I - 1.5}{0.6}, x_3 = \frac{\varphi_{IP} - 155}{15}; \tag{4}$$

– variant MA – 80 Tex meta-aramid complex yarn:

$$x_1 = \frac{P_{0I} - 26}{9},\ x_2 = \frac{R_I - 1.5}{0.6}, x_3 = \frac{\varphi_{IP} - 155}{15}. \tag{5}$$

At the second stage, we determine the tension for the range of changes in the radius of curvature of guide II. Table 3 gives the second-order orthogonal plan matrix for four options KE, CA, PO, and MA.

Table 3

A second-order orthogonal plan matrix for four variants KE, CA, PO, and MA for the range of change in the radius of curvature of guide II

No.	Factor								
	Starting tension					Starting tension		Starting tension	
	x_1	P_{0II}, cN				x_2	R_{II}, mm	x_3	φ_{IIP}, degree
		KE	CA	PO	MA				
1	+1	40	34	22	35	+1	14	+1	105
2	–1	24	18	14	17	+1	14	+1	105
3	+1	40	34	22	35	–1	6	+1	105
4	–1	24	18	14	17	–1	6	+1	105
5	+1	40	34	22	35	+1	14	–1	75
6	–1	24	18	14	17	+1	14	–1	75
7	+1	40	34	22	35	–1	6	–1	75
8	–1	24	18	14	17	–1	6	–1	75
9	–1.215	22	16	13	15	0	10	0	90
10	+1.215	42	36	23	37	0	10	0	90
11	0	32	26	18	26	–1.215	5	0	90
12	0	32	26	18	26	+1.215	15	0	90
13	0	32	26	18	26	0	10	–1.215	72
14	0	32	26	18	26	0	10	+1.215	108
15	0	32	26	18	26	0	10	0	90

The relationship between named and coded values for the range of changes in the radius of curvature of guide II for chemical complex threads is as follows:

– variant KE – Kevlar complex thread 68 Tex:

$$x_1 = \frac{P_{0II} - 32}{8},\ x_2 = \frac{R_{II} - 10}{4},\ x_3 = \frac{\varphi_{IIP} - 90}{15}; \tag{6}$$

– variant CA – H-70 carbon filament with a thickness of 70 Tex:

$$x_1 = \frac{P_{0II} - 26}{8},\ x_2 = \frac{R_{II} - 10}{4},\ x_3 = \frac{\varphi_{IIP} - 90}{15}; \tag{7}$$

– variant PO – polyethylene complex yarn 88 Tex:

$$x_1 = \frac{P_{0II} - 18}{4}, x_2 = \frac{R_{II} - 10}{4}, x_3 = \frac{\varphi_{IIP} - 90}{15}; \tag{8}$$

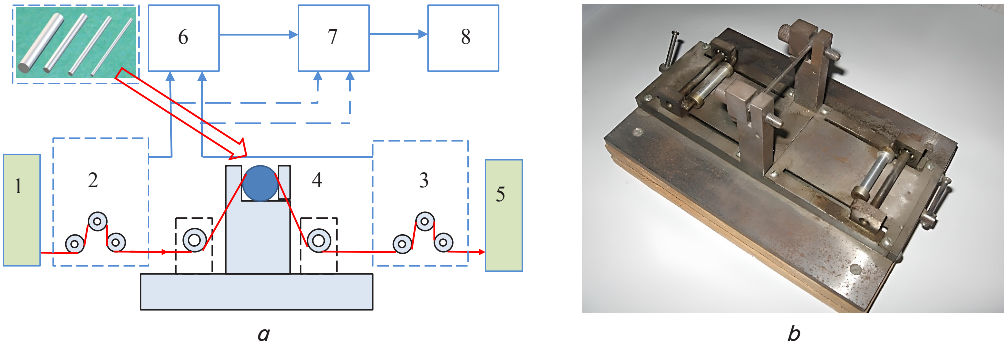
– variant MA – 80 Tex meta-aramid complex yarn:

$$x_1 = \frac{P_{0II} - 26}{9}, x_2 = \frac{R_{II} - 10}{4}, x_3 = \frac{\varphi_{IIP} - 90}{15}. \tag{9}$$

Fig. 4, *a* shows the schematic diagram of the experimental setup. The first block 1 is a device for feeding and tensioning Kevlar, carbon, polyethylene, and meta-aramid complex threads. The input tension was created with the help of a tensioner. The second 2 and third 3 blocks are intended for measuring the tension of the driven and leading branches of Kevlar, carbon, polyethylene, and meta-aramid complex threads 9. They include two rollers that are installed in bearings on fixed axes. The third roller is mounted on a cantilevered beam in such a way that the inner ring of the bearing is fixed on it, and a roller interacting with Kevlar, carbon, polyethylene, and meta-aramid complex threads is rigidly fixed to the outer ring of the bearing. Frictional forces in the bearings are neglected. The warp thread was inserted into the pulleys in such a way that the leading and trailing branches were located on the sides of the isosceles triangle. Under the action of tension of Kevlar, carbon, polyethylene, and meta-aramid complex threads, bending of the middle rod occurred, which led to a change in the resistance of the sensor. This was recorded on the corresponding channel of the 8ANCH-7M amplifier. The transverse and longitudinal dimensions of the beam are chosen such that the frequency of the beam's natural oscillations is 1400 Hz. This frequency is many times higher than the frequency of the highest tension component.

Fig. 4, *b* presents the central measuring node 4 of the experimental setup. It is intended for modeling the conditions of interaction of Kevlar, carbon, polyethylene, and meta-aramid complex threads 9 with cylindrical guides. Two sliding pairs are installed on the frame in horizontal grooves, on which aluminum rollers are fixed in rotation bearings. The position of the sliding pairs relative to the central fixed bracket is changed with the help of two screw pairs by turning two levers on the left and right. The central, stationary vertical bracket is used to fasten cylindrical guides of different diameters. Fastening is carried out with the help of two pairs of screws and clamping bars.

The feed rate of Kevlar, carbon, polyethylene, and meta-aramid complex threads 9 was varied with the help of a stepped circular belt transmission – block 5 in Fig. 4, *a*. The drive pulley of this transmission received rotation from the AC motor, which was rigidly attached to the frame of the main measuring complex. Analog signals from 3 and 4 thread tension measuring units are sent to amplifier 6 or to analog-to-digital converter 7. The analog-to-digital converter is a multifunctional board L-780M with a 14-bit/400 kHz ADC signal processor, with 16 differential input analog and output digital channels, which is installed in the PCI connector of personal computer 8.



a *b*

Fig. 4. Schematic of the experimental setup: *a* — schematic diagram: 1 — thread feeding unit; 2 — unit for measuring the tension of the driven branch of the thread; 3 — unit for measuring the tension of the leading branch of the thread; 4 — block of modeling of the conditions of interaction with the guiding and working bodies of textile machines; 5 — thread receiving unit; 6 — amplifier; 7 — analog-digital converter; 8 — personal computer; 9 — thread; *b* — the central measuring node

5. Results of research on determining the tension of complex chemical threads when interacting with guiding surfaces

5. 1. Results of the determination of the tension of complex chemical threads for range I

As a result of the implementation of the experimental plans (Tables 2, 3) for four options KE, CA, PO, and MA for the range of changes in the radius of curvature of guide I, 10 parallel measurements were carried out, the average values of which are given in Table 4.

Table 4

Results of determining the tension for four options KE, CA, PO, and MA for the range of changes in the radius of curvature of guide I

Experiment No.	Tension of the warp thread at the exit from zone *Pi*, cN			
	KE – Kevlar complex thread 68 Tex	CA – 70 Tex thick H-70 carbon filament	PO – polyethylene complex yarn 88 Tex	MA – meta-aramid complex filament 80 Tex
	i=I	*i*=I	*i*=I	*i*=I
1	66.41	52.49	32.92	49.80
2	40.14	28.00	21.06	24.36
3	76.74	59.38	36.93	55.06
4	46.45	31.72	23.65	26.98
5	61.65	49.24	31.03	47.28
6	37.21	26.23	19.83	23.10
7	70.98	55.54	34.71	52.16
8	42.92	29.63	22.21	25.53
9	36.95	24.98	19.62	21.57
10	69.92	55.69	34.49	52.73
11	61.32	45.39	30.18	40.92
12	51.11	38.84	26.14	36.03
13	51.09	38.82	26.11	36.02
14	55.96	41.98	28.06	38.38
15	53.47	40.37	27.07	37.18

Using a known procedure for determining the coefficients in the regression equation (1) for the orthogonal plan of order 2 [4, 5, 7–12], taking into account the dependences (2) to (9), the regression dependences were obtained. The adequacy of our regression dependences was checked using the SPSS program for statistical processing of experimental data [7, 9–11].

For the range of changes in the radius of curvature of guide I:

– variant KE – Kevlar complex thread 68 Tex:

$$P_I = 18.12 + 1.27P_{0I} - 11.17R_I - 0.12\varphi_{PI} - 0.20P_{0I}R_I + \\ + 0.004P_{0I}\varphi_{PI} - 0.02R_I\varphi_{PI} + 0.0008P_{0I}^2 + 4.81R_I^2 + \\ + 0.0005\varphi_{PI}^2; \qquad (10)$$

– variant CA – H-70 carbon filament with a thickness of 70 Tex:

$$P_I = 10.49 + 1.25P_{0I} - 7.31R_I - 0.06\varphi_{PI} - 0.16P_{0I}R_I - \\ - 0.012R_I\varphi_{PI} + 0.0005P_{0I}^2 + 3.03R_I^2 + 0.0003\varphi_{PI}^2; \qquad (11)$$

– variant PO – polyethylene complex yarn 88 Tex:

$$P_I = 7.13 + 1.21P_{0I} - 4.54R_I - 0.043\varphi_{PI} - 0.14P_{0I}R_I + \\ + 0.003P_{0I}\varphi_{PI} - 0.01R_I\varphi_{PI} + 0.001P_{0I}^2 + 1.89R_I^2 + \\ + 0.0001\varphi_{PI}^2; \qquad (12)$$

– variant MA – 80 Tex meta-aramid complex yarn:

$$P_I = 9.10 + 1.19P_{0I} - 5.69R_I - 0.057\varphi_{PI} - 0.12P_{0I}R_I + \\ + 0.003P_{0I}\varphi_{PI} - 0.01R_I\varphi_{PI} + 0.0003P_{0I}^2 + 2.28R_I^2 + \\ + 0.0002\varphi_{PI}^2. \qquad (13)$$

Regression dependences (10) to (13), for range I, make it possible to determine the influence of structural and technological parameters on the amount of tension of chemical threads after the guide.

For the calculated value of the angle of coverage φ_{PI}=155° in the center of the experiment, for the range of change of the radius of curvature of guide I, using the dependences (10) to (13), the following system of equations is buit:

– variant KE – Kevlar complex thread 68 Tex:

$$P_I = 11.53 + 1.92P_{0I} - 14.27R_I - \\ - 0.20P_{0I}R_I + 0.0008P_{0I}^2 + 4.81R_I^2; \qquad (14)$$

– variant CA – H-70 carbon filament with a thickness of 70 Tex:

$$P_I = 8.39 + 1.25P_{0I} - 9.17R_I - \\ - 0.16P_{0I}R_I + 0.0005P_{0I}^2 + 3.03R_I^2; \quad (15)$$

– variant PO – polyethylene complex yarn 88 Tex:

$$P_I = 2.87 + 1.68P_{0I} - 6.09R_I - \\ - 0.14P_{0I}R_I + 0.001P_{0I}^2 + 1.89R_I^2; \quad (16)$$

– variant MA – 80 Tex meta-aramid complex yarn:

$$P_I = 5.07 + 1.66P_{0I} - 7.24R_I - \\ - 0.12P_{0I}R_I + 0.0003P_{0I}^2 + 2.28R_I^2. \quad (17)$$

The adequacy of our regression dependences (14) to (17) was checked using the SPSS program for statistical processing of experimental data [7, 9–11].

Using the dependences (14) to (17), response surfaces were constructed for the range of changes in the radius of curvature of guide I. Fig. 5 shows graphical dependences: Fig. 5, *a* – for Kevlar complex thread 68 Tex; Fig. 5, *b* – for H-70 carbon thread with a thickness of 70 Tex; Fig. 5, *c* – for polyethylene complex thread 88 Tex; Fig. 5, *d* – for meta-aramid complex thread 80 Tex.

The optimal value of the radius of curvature of the guide, at which the output value of the tension will have a minimum value, for range I will be 2.29 mm, for range II the optimal value of the radius of curvature of the guide will be 14.84 mm. The decrease in the value of the output tension of the chemical threads for range II is explained by a decrease in the specific pressure in the contact zone, a decrease in the influence of the bendability of the chemical threads by the value of the real angle of coverage.

5. 2. Results of research on determining the tension of complex chemical threads for range II

As a result of the implementation of the experimental plans (Tables 2, 3) for four options KE, CA, PO, and MA for the range of changes in the radius of curvature of guide II, 10 parallel measurements were carried out, the average values of which are given in Table 5.

Table 5

Results of determining the tension for four options KE, CA, PO, and MA for the range of changes in the radius of curvature of guide II

Experiment No.	Tension of the warp thread at the exit from zone *Pi*, cN			
	KE – Kevlar complex thread 68 Tex	CA – 70 Tex thick H-70 carbon filament	PO – polyethylene complex filament 88 Tex	MA – 80 Tex meta-aramid complex filament
	i=II	*i*=II	*i*=II	*i*=II
1	52.62	43.02	27.16	42.37
2	31.70	22.87	17.33	20.66
3	53.34	43.52	27.45	42.77
4	32.14	23.14	17.51	20.86
5	48.83	40.34	25.65	40.22
6	29.38	21.42	16.35	19.59
7	49.54	40.84	25.93	40.62
8	29.81	21.69	16.53	19.79
9	28.10	19.75	15.68	17.81
10	53.40	44.23	27.66	43.74
11	41.42	32.45	21.94	31.13
12	40.59	31.89	21.61	30.70
13	38.97	30.80	20.94	29.84
14	42.64	33.27	22.44	31.77
15	40.76	32.01	21.68	30.79

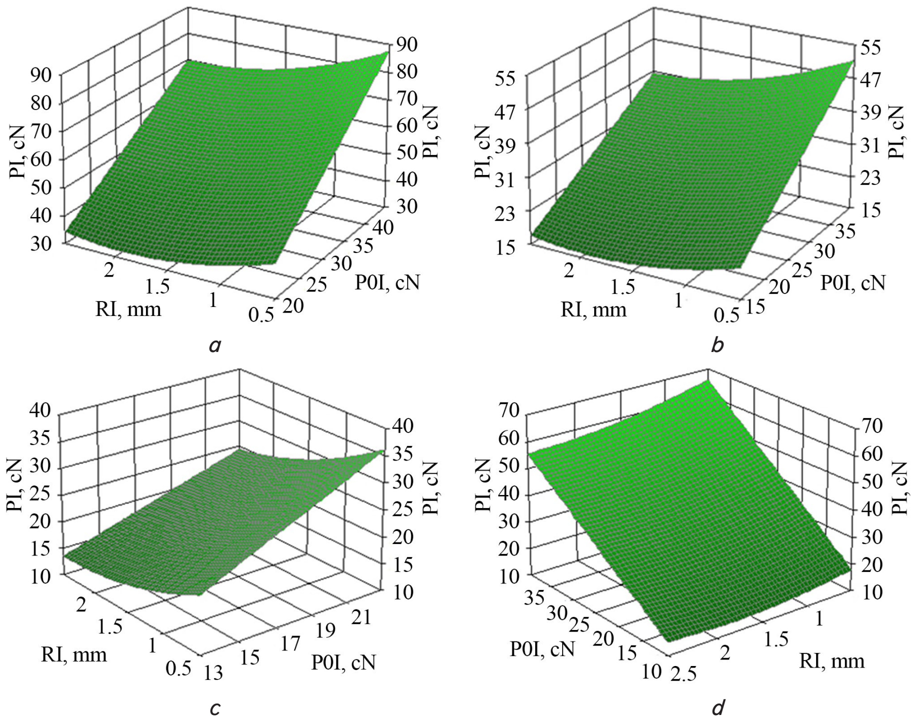


Fig. 5. Graphical dependences of the thread tension of the base for the range of changes in the radius of curvature of guide I: *a* – Kevlar complex thread 68 Tex; *b* – H-70 carbon fiber with a thickness of 70 Tex; *c* – polyethylene complex thread 88 Tex; *d* – meta-aramid complex thread 80 Tex

For the range of changes in the radius of curvature of guide II:

– variant KE – Kevlar complex thread 68 Tex:

$$P_{II}=1.88+1.01P_{0II}-0.17R_{II}-0.02\varphi_{PII}-$$
$$-0.02P_{0II}R_{II}+0.003P_{0II}\varphi_{PII}-0.0001R_{II}\varphi_{PII}-$$
$$-0.0002P_{0II}^2+0.01R_{II}^2+0.0001\varphi_{PII}^2; \qquad (18)$$

– variant CA – H-70 carbon filament with a thickness of 70 Tex:

$$P_{II}=1.88+1.01P_{0II}-0.11R_{II}+1.67\varphi_{PII}-$$
$$-0.002P_{0II}R_{II}+0.003P_{0II}\varphi_{PII}-0.0002P_{0II}^2+$$
$$+0.006R_{II}^2+0.00004\varphi_{PII}^2; \qquad (19)$$

– variant PO – polyethylene complex yarn 88 Tex:

$$P_{II}=0.58+1.03P_{0II}-0.07R_{II}-0.004\varphi_{PII}-$$
$$-0.002P_{0II}R_{II}+0.002P_{0II}\varphi_{PII}-0.00002R_{II}\varphi_{PII}-$$
$$-0.0003P_{0II}^2+0.004R_{II}^2+0.00003\varphi_{PII}^2; \qquad (20)$$

– variant MA – 80 Tex meta-aramid complex yarn:

$$P_{II}=1.24+1.01P_{0II}-0.09R_{II}-0.01\varphi_{PII}-$$
$$-0.002P_{0II}R_{II}+0.002P_{0II}\varphi_{PII}-0.0001P_{0II}^2+$$
$$+0.005R_{II}^2+0.00004\varphi_{PII}^2. \qquad (21)$$

Regression dependences (18) to (21), for range II, allow determining the influence of structural and technological parameters on the amount of tension of chemical threads after the guide.

For the calculated value of the coverage angle φ_{PII}=90° in the center of the experiment, for the range of change of the radius of curvature of guide II, using the dependences (18) to (21), the following system of equations is built:

– variant KE – Kevlar complex thread 68 Tex:

$$P_{II}=0.89+1.28P_{0II}-0.18R_{II}-$$
$$-0.002P_{0II}R_{II}-0.0008P_{0II}^2+0.01R_{II}^2; \qquad (22)$$

– variant CA – H-70 carbon filament with a thickness of 70 Tex:

$$P_{II}=0.78+1.24P_{0II}-0.11R_{II}-$$
$$-0.002P_{0II}R_{II}-0.0002P_{0II}^2+0.006R_{II}^2; \qquad (23)$$

– variant PO – polyethylene complex yarn 88 Tex:

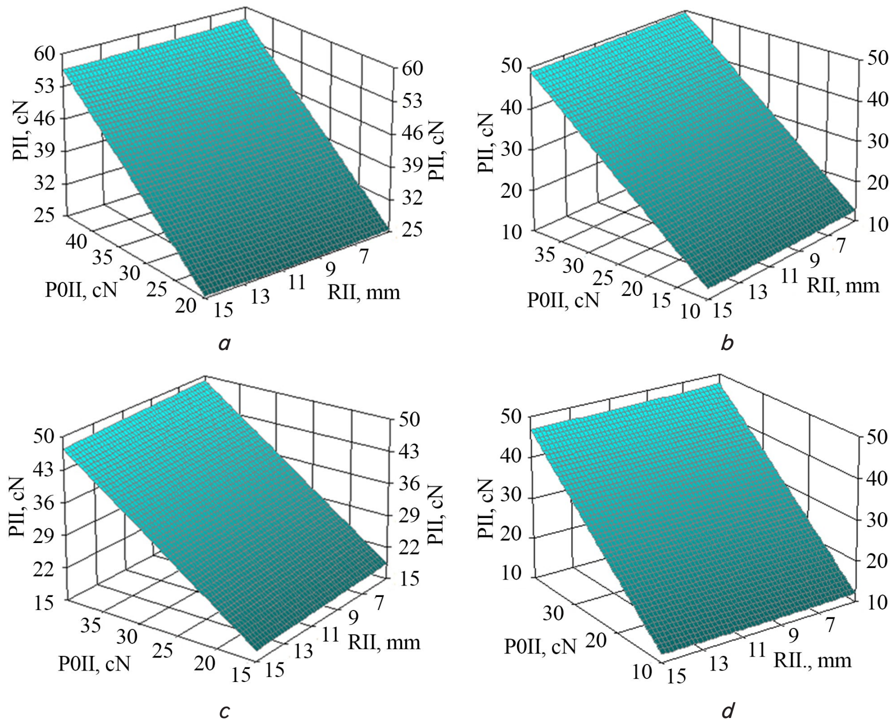
$$P_{II}=0.46+1.23P_{0II}-0.07R_{II}-$$
$$-0.002P_{0II}R_{II}-0.0003P_{0II}^2+0.004R_{II}^2; \qquad (24)$$

– variant MA – 80 Tex meta-aramid complex yarn:

$$P_{II}=0.66+1.19P_{0II}-0.09R_{II}-$$
$$-0.002P_{0II}R_{II}-0.0001P_{0II}^2+0.005R_{II}^2. \qquad (25)$$

The adequacy of our regression dependences (22) to (25) was checked using the SPSS program for statistical processing of experimental data [7, 9–11].

Using the dependences (22) to (25), response surfaces were constructed for the range of changes in the radius of curvature of guide II. Fig. 6 shows graphical dependences: Fig. 6, *a* – for Kevlar complex thread 68 Tex; Fig. 6, *b* – for H-70 carbon thread with a thickness of 70 Tex; Fig. 6, *c* – for polyethylene complex thread 88 Tex; Fig. 6, *d* – for meta-aramid complex thread 80 Tex.



a *b* *c* *d*

Fig. 6. Graphical dependences of the thread tension of the base for the range of changes in the radius of curvature of guide II: *a* – Kevlar complex thread 68 Tex; *b* – H-70 carbon fiber with a thickness of 70 Tex; *c* – polyethylene complex thread 88 Tex; *d* – meta-aramid complex thread 80 Tex

The dependences of the tension of Kevlar, carbon, polyethylene, and meta-aramid complex threads on the radius of curvature of the guiding surface at a fixed value of the input tension were determined. This tension value corresponded to the center of the experiment (Tables 2, 3) for each type of thread. Regression dependences (18) to (21) for the range of changes in the radius of curvature of guide I are transformed into the form:

– variant KE – Kevlar complex thread 68 Tex:

$$P_I = 73.79 - 20.67R_I + 4.81R_I^2; \tag{26}$$

– variant CA – H-70 carbon filament with a thickness of 70 Tex:

$$P_I = 41.24 - 13.33R_I + 3.03R_I^2; \tag{27}$$

– variant PO – polyethylene complex yarn 88 Tex:

$$P_I = 33.34 - 8.61R_I + 1.89R_I^2; \tag{28}$$

– variant MA – 80 Tex meta-aramid complex yarn:

$$P_I = 48.30 - 10.36R_I + 2.28R_I^2. \tag{29}$$

Fig. 7 shows graphical dependences of the influence of the radius of the guide on the tension of Kevlar, carbon, polyethylene, and meta-aramid complex threads for range I. The plots were obtained using dependences (26) to (29).

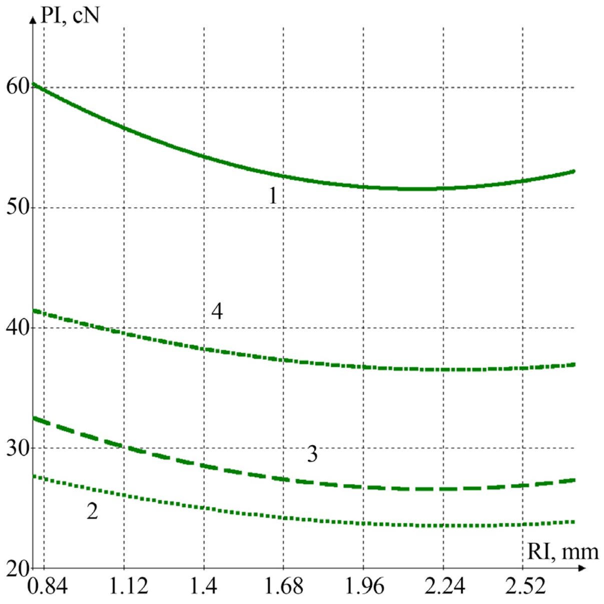


Fig. 7. Dependence of the tension of Kevlar, carbon, polyethylene, and meta-aramid complex threads on the radius of curvature of the guide for the range of changes in the radius of curvature of guide I: 1 — Kevlar complex thread 68 Tex; 2 — carbon fiber H-70 with a thickness of 70 Tex; 3 — polyethylene complex thread 88 Tex; 4 — meta-aramid complex thread 80 Tex

Regression dependences (22) to (25) for the range of changes in the radius of curvature of guide II are transformed into the form:

– variant KE – Kevlar complex thread 68 Tex:

$$P_{II} = 41.65 - 0.25R_{II} + 0.01R_{II}^2; \tag{30}$$

– variant CA – H-70 carbon filament with a thickness of 70 Tex:

$$P_{II} = 32.99 - 0.16R_{II} + 0.006R_{II}^2; \tag{31}$$

– variant PO – polyethylene complex yarn 88 Tex:

$$P_{II} = 22.50 - 0.11R_{II} + 0.004R_{II}^2; \tag{32}$$

– variant MA – 80 Tex meta-aramid complex yarn:

$$P_{II} = 31.53 - 0.14R_{II} + 0.005R_{II}^2. \tag{33}$$

Fig. 8 shows graphical dependences of the influence of the radius of the guide on the tension of Kevlar, carbon, polyethylene, and meta-aramid complex threads for the range of changes in the radius of curvature of guide II, which were obtained using dependences (30) to (33).

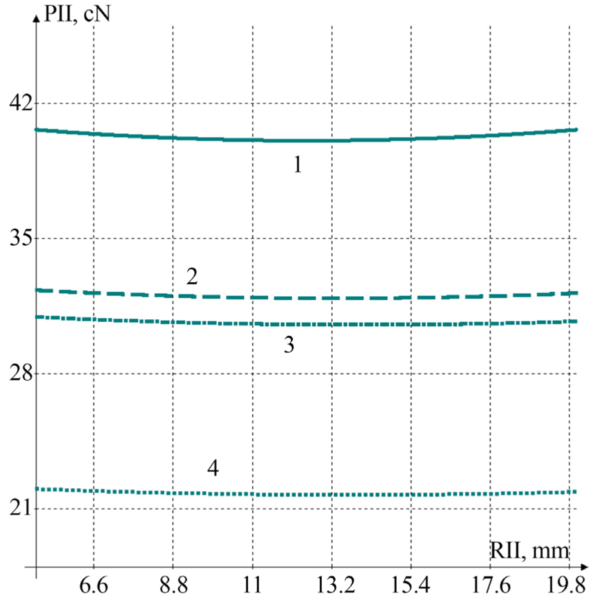


Fig. 8. Dependence of the tension of Kevlar, carbon, polyethylene, and meta-aramid complex threads on the radius of curvature of the guide for the range of changes in the radius of curvature of guide II: 1 — Kevlar complex thread 68 Tex; 2 — carbon fiber H-70 with a thickness of 70 Tex; 3 — polyethylene complex thread 88 Tex; 4 — meta-aramid complex thread 80 Tex

Analysis of the presented graphical dependences in Fig. 7, 8 made it possible to establish the existence of extremum points in which the tension of Kevlar, carbon, polyethylene, and meta-aramid complex threads for the ranges of changes in the radius of curvature of guides I, II will be minimal. This makes it possible to ask the question about the optimization of the geometric dimensions of the guide surfaces of circular knitting and flat knitting machines.

Analysis of graphical dependences in Fig. 8 made it possible to establish that the most intense conditions of interaction with the guide will be for the KE and MA variants in the production of Kevlar meta-aramid knitted fabrics. This is explained by the high value of the stiffness coefficients for stretching and bending of Kevlar complex thread 68 Tex and meta-aramid complex thread 80 Tex.

6. Discussion of results of studying the process of interaction of chemical filaments with guide surfaces

A study was conducted to determine the optimal value of the radius of curvature. This study is aimed at determining the minimum tension value of complex chemical threads made of Kevlar, carbon, polyethylene, and meta-aramid when interacting with the working bodies of large and small curvature of flat knitting and circular knitting machines in the process of forming technical knitwear, in which the tension. Analysis of our results of the dependence of the tension of Kevlar, carbon, polyethylene, and meta-aramid complex threads on the radius of curvature of the guide made it possible to establish that the thread tension increases from zone to zone and reaches its maximum before the knitting zone. It is shown that an excessive value of the tension leads to the violation of the technological process and to the breakage of the thread.

The analysis of equations (26) to (29) showed that when the radius of curvature of the guide decreases, the tension of the chemical threads increases. The increase in tension after the guide surface of a large curvature can be explained by a change in the value of friction forces in the contact zone due to an increase in the real angle of coverage. The analysis of equations (10) to (13) showed that the tension of the selected complex chemical threads after the guide surface of large curvature is affected by the thread tension in front of the guide surface, the radius of curvature of the cylindrical guide surface of the working body, and the angle of coverage of the guide surface by the chemical threads. Table 4 gives the tension values of chemical threads for the I and II range of changes in the radius of curvature of the guide.

For range I of changes in the radius of curvature of the guide surface from 0.8 to 2.2 mm for Kevlar complex thread 68 Tex, the output tension varies from 70.98 cN to 36.95 cN. For range II of changes in the radius of curvature of the guide surface from 5 to 15 mm for Kevlar complex thread 68 Tex, the output tension varies from 49.54 cN to 28.10 cN. The optimal value of the radius of curvature of the guide, at which the output value of the tension will have a minimum value, for range I will be 2.01 mm, for range II the optimal value of the radius of curvature of the guide will be 12.34 mm. For range I of changes in the radius of curvature of the guide surface from 0.8 to 2.2 mm for carbon thread H-70 with a thickness of 70 Tex, the output tension varies from 55.54 cN to 24.98 cN. For range II of changes in the radius of curvature of the guide surface from 5 to 15 mm for carbon thread H-70 with a thickness of 70 Tex, the output tension varies from 40.84 cN to 19.75 cN. The optimal value of the radius of curvature of the guide, at which the output value of the tension will have a minimum value, for range I will be 2.33 mm, for range II the optimal value of the radius of curvature of the guide will be 14.12 mm.

For range I of changes in the radius of curvature of the guide surface from 0.8 to 2.2 mm for the polyethylene complex thread 88 Tex, the output tension varies from 34.71 cN to 19.62 cN. For range II of changes in the radius of curvature of the guiding surface from 5 to 15 mm for polyethylene complex thread 88 Tex, the output tension varies from 25.93 cN to 15.68 cN. The optimal value of the radius of curvature of the guide, at which the output value of the tension will have a minimum value, for range I will be 2.24 mm, for range II the optimal value of the radius of curvature of the guide will be 15.4 mm. For range I of changes in the radius of curvature of the guide surface from 0.8 to 2.2 mm for meta-aramid complex thread 80 Tex, the output tension varies from 52.16 cN to 21.57 cN. For range II of changes in the radius of curvature of the guide surface from 5 to 15 mm for the meta-aramid complex thread 80 Tex, the output tension varies from 40.62 cN to 17.81 cN. The optimal value of the radius of curvature of the guide, at which the output value of the tension will have a minimum value, for range I will be 2.29 mm, for range II the optimal value of the radius of curvature of the guide will be 14.84 mm. The decrease in the value of the output tension of the chemical threads for range II is explained by a decrease in the specific pressure in the contact zone, a decrease in the influence of the bendability of the chemical threads by the value of the real angle of coverage.

The features of our study are the use of guiding surfaces, the radii of curvature of which are identical to the radii of the guiding and working bodies of flat knitting and circular knitting machines (Tables 2, 3). The range of variation of the input tension of the Kevlar complex thread KE was within 22–42 cN, the carbon complex thread CA was within 16–36 cN, the polyethylene complex thread RO was within 13–23 cN, the meta-aramid heat-resistant complex thread MA was within 15–37 cN. For the first range of changes in the radius of curvature of the guide, its value varied from 0.8 mm to 2.2 mm, and the value of the angle covered by the chemical thread of the guide varied in the range of 137–173°. For range II of changes in the radius of curvature of the guide, its value varied from 5 mm to 15 mm, and the value of the angle covered by the chemical thread of the guide varied in the range of 72–108°.

The disadvantages of this method include the impossibility, with this design of the measuring unit, to determine the tension of the chemical threads when guide is displaced in the transverse direction. This is the type of interaction that occurs when threads interact with knitting needles.

A promising area of the current research is the use of guide surfaces of a complex elliptical profile, the cross section of which will be identical to the cross sections of the guide and working bodies.

7. Conclusions

1. For range I of changes in the radius of curvature of the guide surface, regression dependences of the tension of chemical threads on the radius of curvature of the guide, the real angle of coverage of the guide, and the input tension are obtained. For Kevlar complex thread 68 Tex, carbon thread H-70 70 Tex, polyethylene complex thread 88 Tex, and meta-aramid complex thread 80 Tex, the optimal values of the radius of curvature of the guide are determined. For the first range of changes in the radius of curvature of the guide, the radius of the guide surface is commensurate with the calculated radius of the cross section of the thread. At the same time, the tension of Kevlar, carbon, polyethylene, and meta-aramid complex threads to the guide varies within 12 cN $\leq P_{0I} \leq$ 42 cN. The value of the radius of curvature of the guiding surface varies within 0.8 mm $\leq R_I \leq$ 2.2 mm. The value of the angle covered by the thread of the guiding surface varies within $137 \leq \varphi_{PI} \leq 173°$. Due to this, with the use of recursion, it became possible to determine the technological efforts even at the initial stage of designing technological

processes. When producing technical knitwear from Kevlar, carbon, polyethylene, and meta-aramid threads, the optimal geometric and structural parameters of knitting machines were determined.

2. For range II of changes in the radius of curvature of the guide surface, the regression dependences of the tension of chemical threads on the radius of curvature of the guide, the real angle of coverage of the guide, and the input tension were obtained. For Kevlar complex thread 68 Tex, carbon thread H-70 70 Tex, polyethylene complex thread 88 Tex, and meta-aramid complex thread 80 Tex, the optimal values of the radius of curvature of the guide were determined. For the range of changes in the radius of curvature of guide II, the radius of the guide surface significantly exceeds the calculated radius of the cross section of the thread. At the same time, the tension of Kevlar, carbon, polyethylene, and meta-aramid complex threads to the guide varies within $12\text{ cN} \leq P_{0II} \leq 42\text{ cN}$. The value of the radius of curvature of the guide surface varies within $5\text{ mm} \leq R_{II} \leq 15\text{ mm}$, and the value of the angle covered by the thread of the guide surface varies within $72° \leq \varphi_{PII} \leq 108°$. Our results could be used to improve the technological processes of knitting on circular knitting and flat knitting machines.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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