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OPTIMIZATION OF THE DISCRETIZATION PROCESS IN THE PRODUCTION OF AN ELECTRICALLY CONDUCTING HEAT-RESISTANT COMBINATION YARN

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This article is devoted to optimizing the discretization process in the production of electrically conducting heat-resistant combination yarn. Derringer's partial desirability functions are used to solve a multi-criterional optimization problem - select the type of card clothing for the discretizing drum that will provide the best combination of physico-mechanical properties in this type of yarn.

The production of electrically conducting heat-resistant yarn is one of the fastest-growing segments of the textiles industry. Working with the Baranovichi Cotton Production Amalgamation (BCPA), the Department of Spinning of Natural and Chemical Fibers at Vitebsk Technological University has developed a new technology for producing electrically conducting heat-resistant yarns that is based on the card system of cotton-spinning and employs a modernized pneumo-mechanical PPM-120AM spinning machine having a hollow rotor. Arselon fibers and copper micro-wire are the raw materials in the technology. Figure 1 presents a micrograph of a prototype heat-resistant combination yarn.

The electrically conducting yarn can be used to produce textiles that have shielding and anti-static properties. It can also be used to make special high-conductance protective clothing for workers exposed to hazardous conditions – in oil refining and gas- and benzene-processing facilities – and to high-power electromagnetic radiation.

The high heat resistance of Arselon yarn allows products made from it to function at 250°C for a period of up to 3 yrs. These products can be exposed to temperatures of up to 400°C for short periods of time with almost no melting or soot formation. The hygroscopicity of Arselon fibers is close to that of cotton. Arselon yarns' ability to be painted, their low flammability, and the fact that they retain their elastic properties at low temperatures allow them to be used to make fabrics that can be employed in the production of special heat-resistant and low-flammability anti-static and shielding clothing (for firefighters, rescue workers, and equipment technicians), filter cloth for hot gases, and individual protective devices (suits, gloves, mittens) [1]. The physico-mechanical properties of Arselon fibers are shown in Table 1.

Table 2 shows the physico-mechanical properties of the copper micro-wire that is used to make electrically conducting heat-resistant combination yarn.

In the method being proposed here (Fig. 2) for making such yarn, an additional feeder 13 (feed spindles) is used to deliver copper micro-wire 11 to the working zone of the spinning chamber 6 together with the separate flow of Arselon fibers 5 fed from dual-flange reel 12. The micro-wire has a linear density of 18 tex and envelops the yarn 8 that is formed inside the chamber. The resulting heat-resistant electrically conducting combination yarn 9 is led out of the chamber and wound around bobbin 10. The yarn's structure depends on the ratio of the rate of feed of the copper micro-wire to the rate at which the combination yarn is withdrawn from the spinning chamber.

Yarn of moderate linear density is used to make special-use clothing. The BCPA uses yarn with a linear density of 60 tex to convert electrically conducting heat-resistant combination yarn into an assortment of fabrics at its own production facilities.

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TABLE 1. Physico-Mechanical Properties of Arselon Fibers

Parameter	Value
Conditional linear density, elementary fiber, tex	0.17
Deviation of conditional linear density of elementary fiber from the nominal value, %	±8
Staple length, mm	36
Deviation of actual fiber length from the nominal value, %	±8
Unit breaking load for an elementary fiber, mN/tex	280
Oxygen index, %	28
Elongation of elementary fiber at rupture, %	20
Actual moisture content, %, no greater than	14
Mass fraction of lubricant, %	0.5-1.5
Adhesives and roving fibers, %	0.0025
Number of coils per centimeter	3

TABLE 2. Physico-Mechanical Properties of Copper Micro-Wire

Parameter	Value
Nominal diameter, mm	0.04-0.05
Tensile strength of wires of grades MM and MTE, MPa (kgf/mm^2), no less than	441 (45)
Bending resistance, number of cycles	11000
Relative elongation of wires of grades MM and MME, %, no less than	10

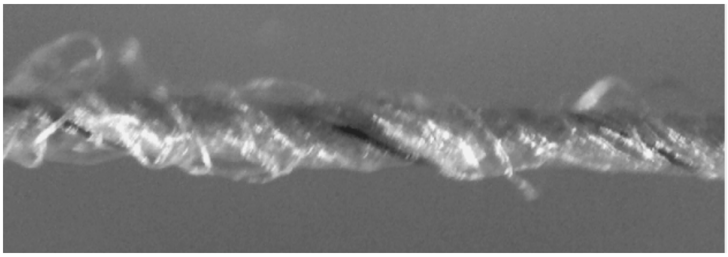


Fig. 1. Micrograph of electrically conducting heat-resistant combination yarn.

The linear density of the given type of yarn is determined from the formula

$$T_{\text{comb}} = (T_{\text{c.wr}} + T_{\text{fb}})K_{\text{ó}}, \tag{1}$$

where T_{comb} is the linear density of the electrically conducting heat-resistant combination yarn, 60 tex; $T_{\text{c.wr}}$ is the linear density of the copper micro-wire, 18 tex; T_{fb} is the linear density of the Arselon fibers, 43 tex; K_{c} is the empirically determined twist-contraction coefficient, equal to 0.98.

One of the main processes that is carried out in pneumo-mechanical spinning [2] is the separation of masses of fibers into individual fibers. This operation is performed by a carding machine.

A carding machine (see Fig. 2) consists of a compacting funnel 2 secured to the feed column of the machine. The strip-shaped mass of fibers 1 is pulled through the funnel. A spring presses the column against feed cylinder 3 to create the necessary pulling force. The feed cylinder presses the strip against discretizing drum 4, which is provided with card clothing. The teeth of the drum separate the continuous flow of fibers into individual fibers and rid them of defects and dirty impurities. The fibers leaving the feed cylinder lose contact with the unseparated strips of fiber and are caught by the teeth of the drum's card clothing. As the drum rotates, the impurities are directed into channel 7, while another

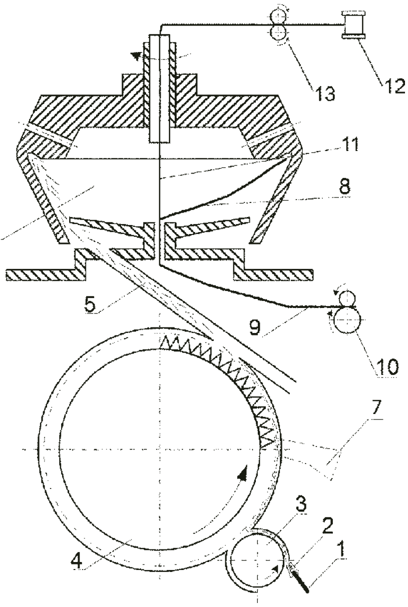
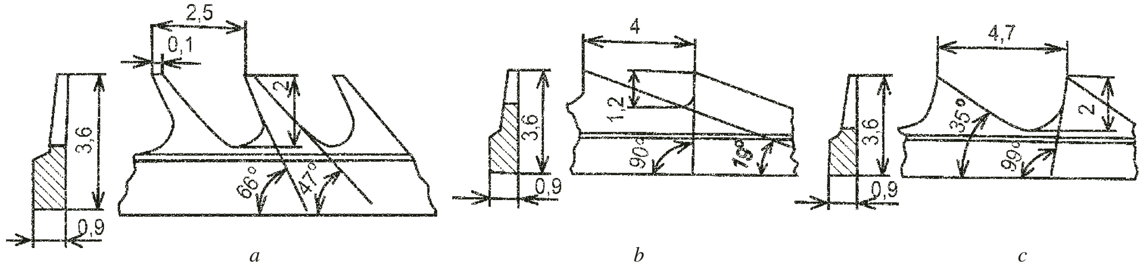


Fig. 2. Schematic diagram of modernized spinning machine PPM-120AM: *1*) fibrous strip; *2*) compacting funnel; *3*) feed cylinder; *4*) discretizing drum; *5*) discrete flow of fibers; *6*) spinning chamber; *7*) channel for removal of impurities; *8*) yarn being formed; *9*) yarn leaving the chamber; *10*) bobbin; *11*) micro-wire; *12*) dual-flange reel; *13*) feed unit.



a *b* *c*

Fig. 3. Card clothing of discretizing drum: a) OK-40; b) OK-36; c) OK-37.

channel transports the fibers to the collecting surface of spinning rotor 6. The fibers are straightened and re-oriented as they move along the channel.

One feature of the discretization process in the processing of Arselon fibers is that the fibers are subjected to mechanical damage, and this is accompanied by a reduction in their length and rejection of some of the product. These developments lower the strength and quality of the yarn. To stabilize the spinning process and improve the quality of the electrically conducting heat-resistant yarn, it is important to ensure that the discretizing component performs in an efficient manner. The main factors that affect the discretization process are the type of card clothing used on the discretizing drum and its speed of rotation (Fig. 3). The card cloth should provide for the necessary degree of separation of the fibers from one another while minimizing the damage done to them in the process.

The intensity with which the teeth of the clothing load each fiber is expressed by the formula

$$m = \frac{znT_\mathrm{f}\,l}{1000\upsilon_\mathrm{f}T_\mathrm{m}}, \tag{2}$$

where z is the number of teeth on the surface of the card clothing; n is the speed of rotation of the discretizing drum, 7000 min^{-1}; T_f is the linear density of the fibers, 0.17 tex; T_m is the linear density of the fiber strip, 5400 tex; l is the average length of the fibers on the feed belt, 36 mm; v_f is the linear feed rate, 0.36 m/min.

TABLE 3. Geometric Parameters of the Card Clothing Being Used

Parameters of card clothing	Type of card clothing		
	OK-40	OK-37	OK-36
Overall height of clothing, mm	3.6	3.6	3.6
Height of teeth, mm	2	2	1.2
Thickness of base of clothing, mm	0.9	0.9	0.9
Pitch of teeth, mm	2.5	4.7	4
Angle of inclination of leading edge, deg	66	99	90
Width of crest of teeth, mm	0.1	0.1	0.1
Thickness of crest of teeth, mm	0.15	0.1	0.2
Width of teeth, mm	0.96	1.13	1.28
Thickness of teeth, mm	0.4	0.4	0.4
Number of teeth on the surface of the discretizing drum	729	388	455
Number of teeth on the drum per fiber	16	8.5	10

The number of teeth on the surface of the drum is calculated from the formula

$$z=\frac{\pi dk}{h_3}, \qquad (3)$$

where k is the number of rotations of the serrated card clothing; h_t is the pitch of the teeth, mm; d is the diameter of the surface of the drum.

Table 3 shows results obtained from calculation of the rate at which the teeth of the clothing load the Arselon fibers and the geometric parameters of the types of clothing that were examined.

We used the following process parameters to make electrically conducting heat-resistant combination yarn with a linear density of 60 tex: density of the strip of fibers T_1 = 5400 tex; rotary speed of the discretizing drum n = 7000 min^{-1}; strip feed rate v_f = 0.36 m/min

The PPM machines installed at the Baranovichi CPA employ three types of card clothing (see Fig. 3). Preliminary tests established that the yarn obtained with the use of each of these types of clothing has acceptable physico-mechanical properties. Although pair-wise comparisons were made of these yarns, it was not possible to determine the type of clothing that is best in regard to all of the main physico-mechanical properties (the coefficients of variation for linear density, twist contraction, and breaking load and the value of the relative breaking load). Thus, the given problem needs to be solved by multi-criterional optimization - selection of the type of card clothing which ensures the best combination of physico-mechanical properties in the electrically conducting heat-resistant combination yarn that is produced.

We performed single-factor (type of card clothing) experiments using the types of clothing currently used on the discretizing drum (types OK-40, OK-36, and OK-37). Table 3 shows the main geometric and technological parameters of these three clothing types.

The experiments were performed at the Baranovichi CPA on modernized pneumo-mechanical spinning machine PPM-120AM.

The three types of clothing were used in succession on the discretizing drums as the yarns were being processed. The main physico-mechanical indices of the yarn were determined [3] in the industrial laboratory at the Baranovichi plant. The following indices were chosen as the optimization criteria: P_1 - the relative breaking load, cN/tex; C_{vb} - the coefficient of variation for the breaking load, %; C_{vd} - the coefficient of variation for linear density, %; C_{vt} - the coefficient of variation for twist contraction, %. The results of the tests are shown in Table 4.

It is apparent from Table 4 that the strongest yarn was obtained using card clothing OK-37 (P_1 = 8.3 cN/tex), the yarn with the lowest coefficient of variation for the breaking load was obtained using the OK-36 clothing (C_{vb} = 6.7%), the yarn with the lowest coefficient of variation for twist contraction was obtained with clothing OK-40 (C_{vt} = 2.4%), and the yarn with the lowest coefficient of variation for linear density was obtained with clothing OK-36 (C_{vd} = 2.8%).

TABLE 4. Physico-Mechanical Properties of Yarn Made Using Discretizing Drums with Different Types of Card Clothing

Criteria	Type of card clothing		
	OK-40 (X_1)	OK -37 (X_2)	OK-36 (X_3)
Coefficient of variation of linear density (Y_1), %	3.2	3	2.8
Coefficient of variation of twist contraction (Y_2), %	2.4	2.9	2.7
Coefficient of variation of breaking load (Y_3), %	10	8.1	6.7
Relative breaking load (Y_4), cN/tex	8.1	8.3	7.7

TABLE 5. Desirability Limits of Partial Optimization Criteria

Criteria	Value of criterion	
	least desirable (0)	most desirable (1)
Coefficient of variation of linear density (Y_1), %	3.5	2.5
Coefficient of variation of twist contraction (Y_2), %	3.5	2.5
Coefficient of variation of breaking load (Y_3), %	10.5	5
Relative breaking load (Y_4), cN/tex	7.5	8.5

Thus, it is impossible to choose a card clothing that will ensure the best physico-mechanical properties for the electrically conducting heat-resistant yarn based on all of the given criteria simultaneously. We therefore resorted to the method of generalized desirability functions to solve the optimization problem.

In order to jointly examine criteria that have different units of measurement, it is necessary to convert them to dimensionless form by using Derringer's partial desirability functions [4]. Table 5 shows the ranges of values for these functions.

The criteria Y_1, Y_2, and Y_3 have upper bounds. Their desirability is determined from the formula

$$d_i = \begin{cases} 1 & \text{при } Y_i < L_{Y_i} \\ \left(\dfrac{Y_i - U_{Y_i}}{L_{Y_i} - U_{Y_i}} \right)^{r_{Y_i}} & \text{при } L_{Y_i} \le Y_i \le U_{Y_i} \;, \\ 0 & \text{при } Y_i > U_{Y_i} \end{cases} \qquad (4)$$

where i is the number of the given criterion ($i = 1.3$); r_{Yi} is the parameter that determines the curvature of the desirability function ($r_{Yi} = 1$).

Since the values of the criteria Y_1, Y_2, and Y_3 are within the indicated ranges, their desirability is calculated from the formulas

$$d_1 = \frac{Y_1 - 3.5}{2.5 - 3.5}, \; d_2 = \frac{Y_2 - 3.5}{2.5 - 3.5}, \; d_3 = \frac{Y_3 - 10.5}{5 - 10.5}. \qquad (5)$$

The criterion Y_4 is bounded from below, and its desirability is determined from the formula

$$d_4 = \begin{cases} 0 & \text{at } \; Y_4 < L_{Y4} \\ \left(\dfrac{Y_4 - L_{Y_4}}{U_{Y_4} - L_{Y_4}} \right)^{l_{Y4}} & \text{at } \; L_{Y_4} \le Y_4 \le U_{Y_4} \\ 1 & \text{at } \; Y_4 > U_{Y_4} \end{cases} \qquad (6)$$

where l_{Y4} is the parameter that determines the curvature of the desirability function ($l_{Y4} = 1$).

TABLE 6. Partial Desirabilities of Physico-Mechanical Properties of Yarn

Criteria	Value of criterion		
	OK-40 (X_1)	OK-37 (X_2)	OK-36 (X_3)
Coefficient of variation of linear density (Y_1), %	$d_{1,1} = 0.3$	$d_{1,2} = 0.5$	$d_{1,3} = 0.7$
Coefficient of variation of twist contraction (Y_2), %	$d_{2,1} = 1$	$d_{2,2} = 0.6$	$d_{2,3} = 0.8$
Coefficient of variation of breaking load (Y_3), %	$d_{3,1} = 0.09$	$d_{3,2} = 0.44$	$d_{3,3} = 0.69$
Relative breaking load (Y_4), cN/tex	$d_{4,1} = 0.6$	$d_{4,2} = 0.8$	$d_{4,3} = 0.2$

TABLE 7. Values of the Generalized Desirability Function

Type of card clothing	Desirability
OK-40	$D_1 = \left(d_{1,1} \cdot d_{2,1} \cdot d_{3,1} \cdot d_{4,1}\right)^{1/4} = 0.35766$
OK-37	$D_2 = \left(d_{1,2} \cdot d_{2,2} \cdot d_{3,2} \cdot d_{4,2}\right)^{1/4} = 0.568873$
OK-36	$D_3 = \left(d_{1,3} \cdot d_{2,3} \cdot d_{3,3} \cdot d_{4,3}\right)^{1/4} = 0.527424$

TABLE 8. Physico-Mechanical Properties of Heat-Resistant Electrically Conducting Yarn

Parameter	Value
Linear density, tex	60
Coefficient of variation of linear density, %	3
Breaking load, cN	498
Coefficient of variation of breaking load, %	8.1
Elongation at rupture, %	14
Coefficient of variation of elongation at rupture, %	14.5
Diameter of yarn, mm	0.155
Twist contraction, twists/m	950
Oxygen index, %	27
Resistivity, Ω	$2.5 \cdot 10^2$

The values of the criterion Y_4 are also located within the range indicated for l_{Y4}, and its desirability is calculated from the formula

$$d_4 = \frac{Y_4 - 7.5}{8.5 - 7.5}. \tag{7}$$

Table 6 shows the desirability values of the criteria calculated from Eqs. (5) and (7).

The generalized desirability function - which accounts for the desirability of each partial optimization criterion - has the form

$$D_{i,j} = \sqrt[n]{\prod_{i=1}^{n} d_{i,j}}\,, \tag{8}$$

where n is the number of partial optimization parameters that are examined, n being equal to 4 in our case; $d_{i,j}$ is the desirability of the i-th partial optimization criterion for the j-th card clothing.

Thus, the optimization problem reduces to determining the maximum value of generalized desirability function D.

Table 7 shows values of the generalized function calculated for discretizing drums with different types of card clothing.

An analysis of the results permits the conclusion that the most desirable card clothing is OK-37 ($D = 0.56$). Its teeth have a negative angle of inclination of 99° and a pitch of 4.7 mm, and this clothing also has the fewest teeth on the surface of the drum (compared to OK-40 and OK-36). Thus, the fibrous tuft is also loaded at a lower rate. Table 8 shows the physico-mechanical properties of electrically conducting heat-resistant yarn obtained with the use of card clothing OK-37 on the discretizing drum.

The completed studies have established that it is best to use card clothing OK-37 to obtain electrically conducting heat-resistant combination yarn. Use of this clothing ensures that the yarn will have the following physico-mechanical properties: relative breaking load 8.3 cN/tex; coefficient of variation for the breaking load 8.1%; coefficient of variation for linear density 3%; coefficient of variation for twist contraction 2.9%.

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