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Досліджено процес формування джгутового намотування з точки зору силових взаємодій ниток. Встановлено, що при певних співвідношеннях між частотою обертання бобіни і частотою руху нитководія відбувається укладання ниток на одне й те саме місце і формується джгутове намотування. Для усунення дефектів у вигляді джгутів та супроводжуючих їх хорд запропоновано зменшити до можливого мінімуму відстань від вічка нитководія до точки набігання

Ключові слова: джгутова намотування, хорда, нитководій, дефекти намотування, точка набігання

Исследован процесс формирования жгутовой намотки с точки зрения силовых взаимодействий нитей. Установлено, что при определенных соотношениях между частотой вращения бобины и частотой движения нитеводителя происходит укладка нитей на одно и то же место и формируются жгутовая намотка. Для устранения дефектов в виде жгутов и сопровождающих их хорд предложено уменьшить до возможного минимума расстояние от глазка нитеводителя до точки набегания

Ключевые слова: жгутовая намотка, хорда, нитеводитель, дефекты намотки, точка набегания

ANALYSIS OF THE FORMATION OF FILAMENT WINDING IN TERMS OF FORCE INTERACTIONS BETWEEN THREADS

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1. Introduction

As it is known [1], filament winding is formed when motion frequency of the yarn guide becomes multiple to the rotation frequency of a bale. Because at frictional winding the speed of bale rotation continuously decreases in a certain range with an increase in diameter, the conditions for the formation of filament structures occur periodically.

The quality of bales is defined by the winding structure, which is closely linked to the shape of a bale. The presence

of winding structure defects increases discontinuities during coiling, which leads to a decrease in the efficiency of warping and weaving. Timely detection of such defects would eliminate the causes of their occurrence through appropriate adjustment of equipment. The bobbins with defects are sent to be rewound. In this case, the costs related to the additional rewinding are considerably lower than those due to the liquidation of breakages in warping and weaving. Thus, creation of a method for automated control over winding structure and its implementation in industry would improve the efficiency of processes of warping and weaving and enhance quality of fabric by eliminating defects related to the liquidation of discontinuities.

Given the above, it is an important task to design automated control over the structure of bale winding formed by machines with a friction drive of bales.

2. Literature review and problem statement

When studying the processes of winding formation, several areas are typically addressed, including a technological aspect of the issue, the impact of materials and design features of mechanisms on the quality of the finished product. The technological aspect is considered through the prism of the influence of technological parameters of the process on errors in winding and in the formation of bales [1–3], however, the choice of materials or taking them into consideration when selecting technological parameters and control methods of the winding process are equally important both in technologies and equipment. Thus, paper [4] describes technologies for manufacturing yarns and threads from which it follows, in particular, that high-performance applications can use technical fibers or high-performance fibers/filaments for the production of threads with the preset properties. It was also noted that the use of multiple thin filaments for the production of sewing thread is crucial for manufacturing a high-performance product. It should be noted that it could be interesting from a practical point of view if the authors provided additional data on relationship between the quality of yarn winding modes. Article [5] argues that the key to the effective functioning of subsequent technological processes is the preparation of yarn. In this case, the authors demonstrated techniques to remove errors and, in this regard, critically analyzed various types of winding machines. The results obtained make it possible, in principle, to get to know the dangers posed by a mismatch between mechanical part of the equipment and requirements of the technological process, as well as deviations in the parameters of the process in terms of quality of the resulting product. It should be emphasized that the conclusions drawn may refer to different threads. However, further attention to structural design of the appropriate mechanisms of winding machines would contribute to the formation of a more systemic view of the process. The latter is particularly important if the priority of functioning of machinery is the quality of the finished product.

The sequence of processes for the production of different types of yarn using machines for winding can be found in paper [6], which pays particular attention to the work of tensioning devices and control over winding process. It is noted that a deviation from the conditions of functioning of corresponding mechanisms can lead to the formation of faults whose description can also be found in [4]. An interesting development of a given study would be to study various types

of mechanisms design and their influence on the choice of control over a technological process of winding. Particularly noteworthy is the possibility of the universality of such a view, which may include the possibility of creating standardized designs for a broader range of application of the winding process. A proof to this can be directions for research into such types of mechanisms for other applied technologies that implement a similar, from the point of view of mechanical understanding, process. Thus, study [7] describes the design, function and a winding device control system used in the robotized technology of filament winding. A winding mechanism designed by the authors ensures good-quality capture and placement, which is enabled by the rational combination of mechanical part of the mechanism and the control system built into a tool to detect slippage of the feed and in order to control the force of a thread/cable feed. The design of an automated fiber-optic coiling machine, presented in [8], makes it possible to wind several different models of coils accurately, and includes active voltage regulation during winding, as well as an automated system for error correction and detection, based on vision to improve reliability. Given such design solutions, the machine has high performance speed minimizing thereby duration of the winding process. Thus, the proposed solutions could possibly be used in the analogs of winding machines for a sufficiently broad scope of application.

As far as the implementation of a technology in the machines with a friction drive of bales is concerned, of special importance is the fact that the mutual arrangement of turns on the body of a winding at a frictional drive of bales is not uniform [9]. Under certain ratios between the speed of bobbin rotation and the frequency of thread feeder motion, the threads are placed on the same place. In this case, there are the so-called filament formations. If the frequencies of bobbin and thread feeder rotation differ slightly from multiple, the turns are arranged close to each other; in this case, a belt winding is formed. The criteria for determining the type of winding are substantiated in [10]. Filament winding is accompanied by a number of phenomena, which exert a negative impact on the quality of the created bales. The first of such phenomena is that the filament winding has a higher specific density. As noted in [11, 12], at a closed winding, which can be considered as an artificially created model of tape winding, specific density can reach up to 0.64 g/cm^3. At the same time, at a wrap-over winding, its magnitude is of order 0.39 g/cm^3. Differences in the density of winding cause defects when a bale is treated with solution [13], leading to varied shades of yarn from different layers of winding [14]. The authors note that the filament winding on duck-type bobbins can cause not only fabric striation, but also different width of fabric. The difference in density of different layers can be the reason for that the winding loses its stability [15].

The second undesirable phenomenon that accompanies filament winding is the emergence of an unrounded bale due to uneven arrangement of threads at its surface. When a bobbin rotates during winding, its non-roundness is the cause of oscillation excitation in a winding mechanism [16]. As noted in [17], such oscillations may lead to significant deviation from the technological parameters of winding, sometimes leading to the total disruption of a winding process.

The third undesirable phenomenon occurring in the formation of filament winding is the force interactions along the newly stacked turns against the roughness of a bale relief, as a result of which part of the turns is thrown over the edge of the bale, that is, the chords form [18]. During subsequent

unwinding of a bobbin, they cause enhanced discontinuity of yarn at some winding diameters [19].

The kinematic aspect of filament structure formation is described in detail in paper [9]. However, it was noted long ago that kinematic description does not fully determine the process of formation of filament structures; in this case, of special importance is the force interaction of threads, arranged in a winding [20].

3. The aim and objectives of the study

The aim of present study is to analyze formation of a filament winding in terms of force interactions of threads.

To accomplish the aim, the following tasks have been set:
– a theoretical analysis of the processes occurring in the formation of filament structures in terms of force interaction between threads;
– measurement of twisting stiffness of a thread and an analysis of tearing a thread at lifting angle of the turn equal to zero;
– obtaining an analytic description for calculating the number of uncontrollably stacked turns.

4. Results of research into formation of filament winding in terms of force interactions between threads

It was shown in paper [9] that when the distance around the perimeter of a bale between adjacent turns is reduced to the value that is less than the diameter of the thread, a filament winding is formed. At the same time, in an extreme case, a turn of the thread is placed exactly on the place of the preceding one. However, this phenomenon occurs only if the thread is considered ideal, that is, it has no thickness. Actual processes are somewhat complicated. A thread cannot lie exactly on the place placed earlier, it falls off it. In this case, the turn laid earlier acquires the role of a spreader, in other words, it defines the place of laying a thread on the workpiece. This place can differ significantly from the one dictated by a thread feeder.

The most unpleasant event in this case is that the turns of a thread can extend beyond the end of the winding, creating chords, which, at subsequent unwinding of the bobbin, cause tearing [21].

The process of chord formation continues until the thread, deviating from the normal position set by a thread feeder, and being in a state of unstable equilibrium, flies off the preceding turn. In this case, the law of the layout is restored. The kinematic conditions for a filament winding will disappear by that time due to a growth in the bobbin diameter and a decrease in the frequency of its rotation.

Force equilibrium of thread on the surface of a bale was considered in [9] where the bales were represented as a cylinder or a cone that possesses friction though it has a correct geometrical shape. In the considerations that follow we shall assume that the thread has a cylindrical shape and it is incompressible in the transverse direction. Since the chords form at the moment of unwinding a turn, we shall accept in the first approximation that a lifting angle of the turn is equal to zero, that is, the turn is laid in the plane perpendicular to the axis of the bale.

Fig. 1 shows a bale on the surface of which, at a fixed thread feeder, located at point A, the turns of a winding are placed. Turns 1, 2 and 3 were laid earlier. At current moment, turn 4 is being placed. Under kinematic conditions, cross-section centers of all turns must have the same Z coordinate. However, position at which the turns are stacked one on top of another, is unstable.

The subsequent turn flies off the preceding one and is placed next to it (Fig. 1, on the right). In this case, there occurs force $T\sin\alpha$ that tries to bring the turn back to the position assigned by kinematic conditions. As the number of wound turns grows, force $T\sin\alpha$ increases, which eventually leads to that the turn flies off and gets laid above all that were previously placed, at Z coordinate, the closest to the corresponding coordinate of the first turn. We shall determine conditions under which such a fly-off of the turn occurs, which will make it possible to determine the number of turns that are placed with a violation of the kinematic conditions, that is, without control from a thread feeder. For this purpose, we shall consider cross-section $b-b$ that passes through point M where a thread runs over a bale (Fig. 2).
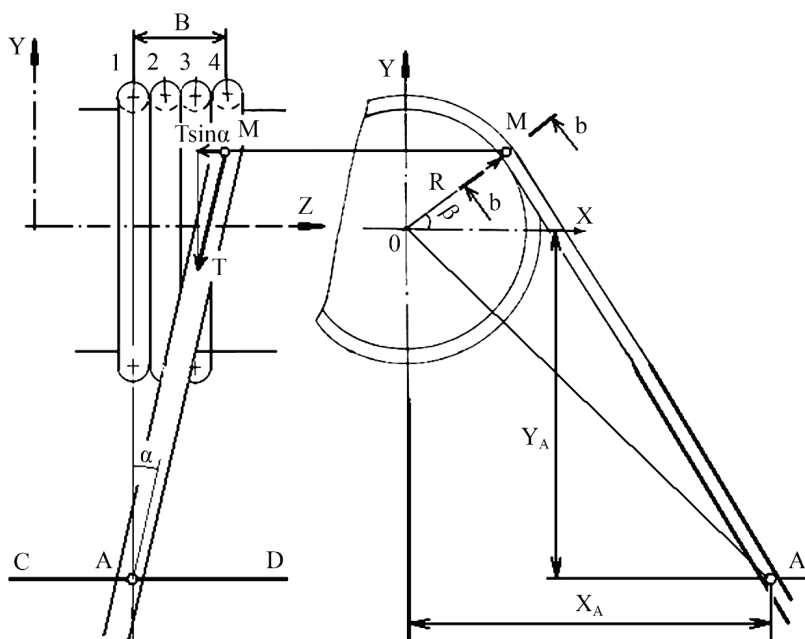

Fig. 1. Schematic of the turns position on the surface a winding at a fixed thread feeder
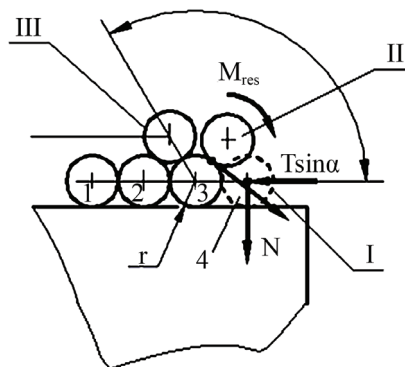

Fig. 2. Arrangement of turns in cross-section $b-b$

A turn in this cross-section can take inclined position I or, in case the turn flies off, position III.

Fig. 2 also shows intermediate position II. We shall determine which forces act on the placed turn in cross-section $b-b$. Inertia forces that acting on a thread are disregarded. In order to calculate a reaction from the body of a winding, we shall determine normal pressure p from the side of the turn on unit length of the surface of a winding body. It is necessary to take into consideration in this case that the winding is applied to a cylindrical surface and, according to the formula by A. P. Minakov [22] for parallel winding:

$$p = \frac{T}{R}. \tag{1}$$

Force N of normal pressure of the placed turn will be considered at the section of its passing the preceding turn 3 (Fig. 1). The length of this section is denoted by S. Fig. 3 shows a scheme to determine length S, it is assumed in this case that the thread is not deformed in the transverse direction.
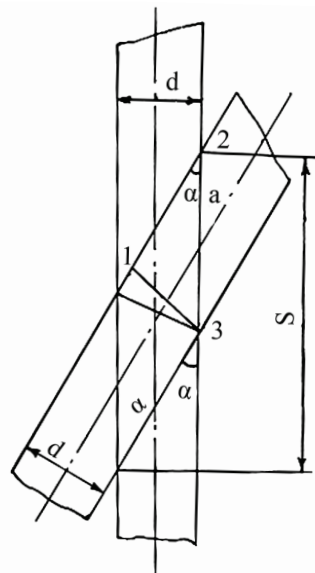

Fig. 3. Arrangement of turns in a transition section

Fig. 3 shows that:

$$S = a\,(1 + \cos\alpha), \tag{2}$$

from $\Delta\,123$

$$a = \frac{d}{\sin\alpha}. \tag{3}$$

By substituting this value in the previous one, we shall obtain:

$$S = \frac{d(1 + \cos\alpha)}{\sin\alpha}. \tag{4}$$

Or, considering the smallness of angle α and that $d = 2r$, we obtain:

$$S = \frac{4r}{\alpha}, \tag{5}$$

a force of normal pressure N, considering Fig. 1, is derived from expression:

$$N = PS = \frac{4Tr}{R\alpha}. \tag{6}$$

Gravity force of the strand is disregarded owing to its smallness compared with thread tension T.

Furthermore, the turn that is being placed is affected by friction force F_{FRIC} and twisting moment M_{RES} caused by elastic twist of the thread.

$$M = c\phi, \tag{7}$$

where ϕ is the twisting angle of the thread; c is the stiffness of the thread at twisting.

The issue about a thread position is solved by finding the work performed by the specified force factors when displacing cross-section $b-b$ from position I to position III.

The work of twisting moment M_{RES} is derived from:

$$A_M = \frac{c\phi^2}{2}. \tag{8}$$

According to Fig. 2, the center of cross-section of turn 4 moves along the arc with a center in the center of cross-section of turn 3 while the cross-section itself rotates by angle:

$$\phi = \frac{2}{3}\pi, \tag{9}$$

$$A_M = C\frac{2}{9}\pi^2.$$

The work of force N when moving from position I to position III is equal to (Fig. 1):

$$A_N = Phs = \frac{4Tr^2}{R\alpha}\sqrt{3}. \tag{10}$$

The work of tension force T to move the cross-section in the transverse direction from position I to position III is determined from:

$$A_T = SrT\sin\alpha$$

or, considering the smallness of angle α:

$$A_T = SrT\alpha. \tag{11}$$

The work of friction force F_{TP} at a point of contact between turns 4 and 3 is not performed because friction force F_{TP} is applied to the instantaneously-fixed point K (we assume that the rolling of cross-section 1 occurs without slippage along cross-section 3). Rolling friction forces are disregarded.

For the center of turn 4 to shift from position I to position II, it is necessary, in accordance with the principle of virtual displacements [23], that the following ratio should hold:

$$A_T > A_M + A_N. \tag{12}$$

By substituting in (12) values of A_T, A_M and A_N from (11), (9) and (10), we shall obtain:

$$SrT\alpha > \frac{2}{9}c\pi^2 + \frac{4T}{R\alpha}r^2\sqrt{3}. \tag{13}$$

Solution to the resulting inequality will take the form:

$$\alpha > \frac{c\pi^2 + \sqrt{c^2\pi^4 + 972r^3T^2\sqrt{3/R}}}{27rT}. \tag{14}$$

The analysis of the obtained formula is advisable to perform using a computer, applying actual values of its constituent magnitudes. All of them, except for thread twisting stiffness, are known when designing a winding mechanism. Basic provisions for the force interactions between threads during formation of a filament winding are given in [24, 25].

A change in thread twisting stiffness and analysis of conditions for a thread fly-off are estimated when lifting angle of the turn is zero. Coefficient c, which is part of formula (14), can be determined experimentally using an expression for period τ of torsional oscillations of a homogeneous rod suspended in the middle (Fig. 4) [26].

$$\tau = \frac{2\pi}{K^2}, \tag{15}$$

where $K^2 = c/J_0$, J_0 is the momentum of inertia of the rod mass. To determine the latter, one can apply formula:

$$J_0 = \frac{Ml^2}{12}, \tag{16}$$

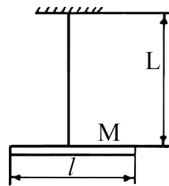where M is the rod mass; l is the rod length.

Fig. 4. Schematic of the set-up for determining thread twisting stiffness

Substituting (16) in expression for K^2, and then the obtained one in (15), we obtain equation:

$$\tau = \frac{2\pi}{\sqrt{\dfrac{12c}{Ml^2}}}. \tag{17}$$

Solve (17) relative c:

$$c = \frac{\pi^2 Ml^2}{3\tau^2}. \tag{18}$$

In the experiment, we used samples of length 245 mm made of twisted cotton yarn produced by the machine PK-100M3 with linear density 25×2 tex, and a plastic rod of length $l=29$ mm and mass $M=940$ mg.

Duration of oscillations was calculated by repeating ten times for five different samples of yarn. The measurement results are summarized in Table 1.

Table 1

Duration of torsional oscillations

Repeated	T, s, for sample					
	1	2	3	4	5	
1	10.2	9.8	9.3	9.1	9.9	
2	9.9	10.2	10.1	9.2	10.4	
3	9.8	10.1	10.2	10.2	9.2	
4	10.1	9.1	9.1	9.9	10.2	
5	10.2	9.9	10.2	10.1	10.1	
6	10.1	10.2	10.0	9.9	9.8	
7	11.0	9.9	9.2	10.2	9.3	
8	9.9	10.1	10.1	10.2	9.1	
9	9.1	9.2	10.1	9.9	9.2	
10	9.1	9.3	10.3	10.4	10.2	
Average τ_i	9.94	9.78	9.87	9.91	9.74	$\tau=9.848$
$(\tau_i-\tau)^2\cdot10^{-3}$	8.46	4.62	0.48	3.84	11.6	$S=4.25$

We shall substitute statistically reliable value $\tau = 9.85 \pm 0.0095$ in formula (18), consequently, we shall obtain a value of c for the respective yarn $c=2.4\cdot10^{-5}$ N·m/rad.

Fig. 5 shows schematic of a winding mechanism of the spinning and twisting machine PK-100M3. By employing formula (14), we shall perform dependence analysis, for a given mechanism, of angle α on the thread tension, diameter of a winding, and thread twisting stiffness. Results of the calculation are shown in charts in Fig. 6, 7.
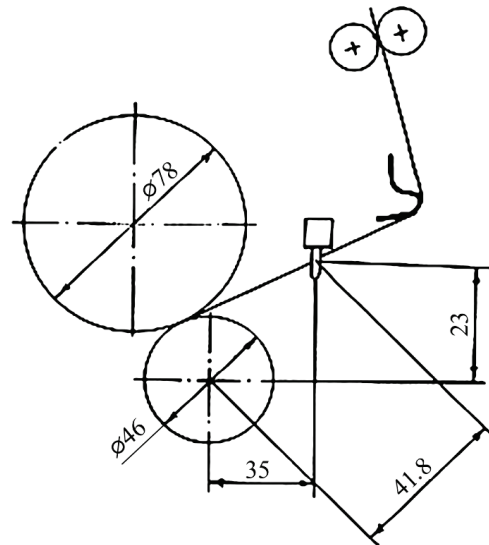

Fig. 5. Schematic of a winding mechanism of the spinning-twisting machine PK-100M3

Charts in Fig. 6 show the largest danger for the formation of fly-offs occurs at small winding diameters and at small tension. With an increase in tension angle α decreases, ultimately approaching to a value close to 4°.

Fig. 7 shows dependences of angle α on winding diameter at different thread twisting stiffness.
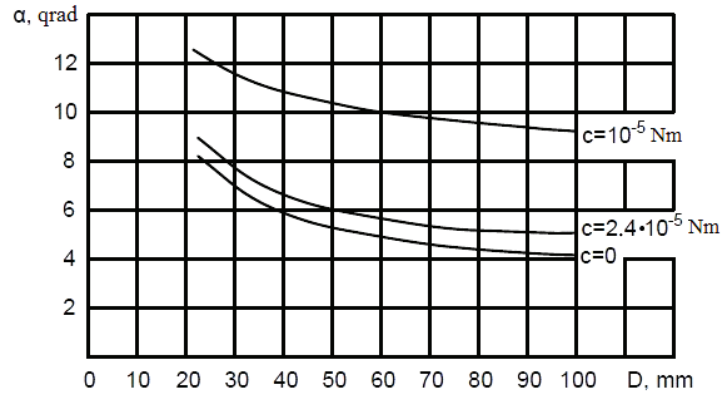
Fig. 6. Dependence of angle α on winding diameter at different tension of thread
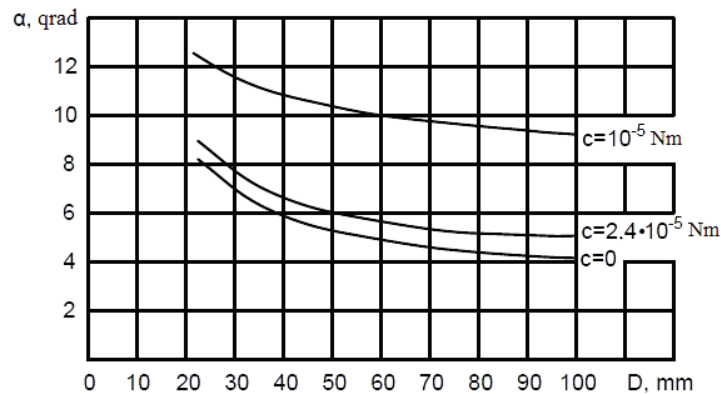

Fig. 7. Dependence of angle α on winding diameter at different thread twisting stiffness

Actual stiffness of the thread used in the experiment was $C = 2.4 \cdot 10^{-5}$ N·m/rad. With an increase in the thread stiffness, control over it by a thread feeder worsens.

The difference between curves corresponding to stiffness $C = 0$ and $C = 2.4 \cdot 10^{-5}$ N·m/rad shows that the effect of stiffness is essential for calculating the possibilities of chord formation on bale ends, caused by loss of control over thread motion by the thread feeder.

5. Discussion of results of research into formation of filament winding

It should be noted that from a practical point of view more important is not the value of angle α but the answer to a question about how many turns of the thread can be wound till the thread flies off from position I to position III (Fig. 2). In other words, how many turns will be laid without control by the thread feeder, with the result being that they can be thrown out of the bale and form chords at the end, which would cause disruption of equipment operation [9].

Let a thread feeder be at point A with coordinates $(X_A; Y_A)$ (Fig. 2). Then the distance at which a thread uncontrolled by a thread feeder can travel:

$$B = MA \sin \alpha. \qquad (19)$$

In triangle ACM, angle OMA is straight, which is why:

$$MA = \sqrt{X_A^2 + Y_A^2 - R^2}.$$

Substituting the expression obtained for MA in (19), we obtain:

$$B = \sqrt{X_A^2 + Y_A^2 - R^2} \sin \alpha. \qquad (20)$$

The number of turns wound without control by the thread feeder,

$$n = \frac{B}{2r} = \frac{\sqrt{X_A^2 + Y_A^2 - R^2}}{2r} \sin \alpha. \qquad (21)$$

$$n = \frac{\sqrt{X_A^2 + Y_A^2 - R^2} \sin \alpha}{2r} \qquad (22)$$

or, ultimately,

$$n = \frac{\left(\dfrac{2}{9} c\pi^2 + \dfrac{T}{R} r \sqrt{3} \right)}{6r^2} \sqrt{X_A^2 + Y_A^2 - R^2}. \qquad (23)$$

A number of uncontrollably wound turns of a thread depends significantly on the magnitude of MA – a distance from the eye of a thread feeder to the point of attack. With a decrease in this distance, control by the thread feeder improves. As shown above, for the winding machine PK-100M3, with a rise in tension angle α stabilizes close to ≈4°. Then, according to equation (23), the number of uncontrollably wound turns at the end will be about 6.

The obtained magnitude corresponds to practical observations of bale formation under industrial conditions. In order to reduce defects for this parameter, it is necessary to set the eye of a thread feeder as close as possible to the bale, which can be done using the machine PK-100M3 when setting the eye similar to that employed by the machines PPM-120. The second important factor is maintaining tension not less than 20 sN for the 25×2 tex yarn. For other linear densities, the required tension can be obtained from formulae (14) and (15). Owing to such design solutions, it is possible to reduce defects in bales, which can be considered an obvious advantage of the present study.

It should also be noted that accounting for a large quantity of design parameters, together with the optimization of the modes of a winding process, could prove useful in terms of the guaranteed improvement of quality. That is why our view of the probable development of present research can be considered viable. Of course, in this case, one should understand that increasing influencing factors complicates the analytical description – estimation formulae. This, in turn, gives rise to difficulties in obtaining equations that would hold because of the need for additional experimental studies. Nevertheless, such an experimental development would be useful even from a point of view of verification of the results obtained on actual equipment against known theoretical models, which were constructed using classical methods of theoretical mechanics.

6. Conclusions

1. We conducted a theoretical analysis of interaction between turns in the formation of filament winding, which made it possible to identify the mechanism of chord formation that leads to thread breaks. It was established, in particular, that this process continues until the thread, deviating from its normal position set by a thread feeder, and while in a state of unstable equilibrium, flies off the preceding turn. The consequence is the restoration of the outlay law, by the time of whose occurrence the kinematic conditions for filament winding disappear due a growth in bobbin diameter and a decrease in the frequency of its rotation.

2. We describe the conditions under which a turn flies off a winding, based on which it is possible to determine the number of turns, placed with a breach of kinematic conditions. It is shown that a given parameter depends on the inclination angle of the turn, and the application of the resulting analytical description of this relation does not present any practical difficulties. The rationale for this argument is the possibility of numerical computer implementation of calculation based on the actual values of its constituent magnitudes, all of which, except for thread twisting stiffness, are known when designing a winding mechanism.

3. It was substantiated that in order to reduce bale defects it is necessary to set the eye of a thread feeder as close as possible to the bale, which can be done using the machine PK-100M3 when setting the eye similar to that employed in the machines PPM-120. In this case, it is also required to maintain tension not less than 20 sN for the yarn 25×2 tex, while for other linear densities this parameter can be calculated based on the obtained analytical dependences for a thread inclination angle and duration of torsional oscillations of a uniform rod suspended in the middle. Such results create a basis of requirements to the design of winding mechanism aimed at reducing the number of uncontrollably placed turns.

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