Представлені матеріали по створенню інструментального методу оцінки опору ниток до ковзаючого вигину щодо циліндричних поверхонь для вирішення завдань контролю і прогнозування умов їх переробки з мінімальними витратами виробництва. Основою методу є диференційований облік енергії, що витрачається на подолання внутрішнього і зовнішнього тертя.

Основним завданням дослідження було підвищення інформативності результатів аналізу волокон і ниток за рахунок прояву фізико-механічних властивостей, обумовлених особливостями їх структури і складом, а також характеристиками огинаємих поверхонь. Запропоновано випробування нитки проводити на основі імітації реальних умов фрикційної взаємодії, при якій радіус заокруглення крайок r робочих органів повинен бути співмірний з товщиною нитки. Стосовно до такого варіанту випробування виявлено умови, що забезпечують прояв параметрів внутрішнього і зовнішнього тертя. Це дозволило розробити технологічну схему випробувань і проведення порівняльних аналізів ниток матеріалів з різною структурою і властивостями.

В якості оцінки, що характеризує прояв тільки зовнішнього тертя по циліндричній поверхні з кривизною 1/r, запропонована величина витраченої енергії $A_{зовн.}$ на переміщення нитки (володіє жорсткістю EI і натягнутою силою) за умови $2T(r)^2/El \geq 1500$. Для обліку сукупної енергії A від зовнішнього і внутрішнього тертя, як оцінки, що характеризує опір нитки до ковзаючого вигину, умови випробування передбачають застосування огинаємої поверхні з підвищеною кривизною $1/r_1$, тобто $r_1 \ll r$.

Для розрахунку оцінки D, як частки енергії $A_{внут.}$ на подолання внутрішнього тертя, застосовують залежність $D=[(A-A_{зовн.})/A]\cdot 100$, %. Запропоновано випробування проводити в два етапи, на кожному з яких натягнута постійною силою нитка повинна при незмінному куті обхвату огинати циліндричні поверхні, але на кожному з етапів їх радіус заокруглення різний.

Ефективність запропонованого методу оцінки опору до ковзаючого вигину підтверджена результатами експериментів. Встановлено можливість диференціації випробовуваних ниток і пряжі за величиною оцінок $A_{зовн.}$ і D в різних умовах взаємодії з циліндричною поверхнею. Отримані результати дозволяють рекомендувати запропонований метод для використання на практиці, а саме, для контролю ступеня прохідності нитки через гарнітуру машин, що проводить нитку

Ключові слова: нитка, ковзаючий вигин, гарнітура, що проводить нитку, витрачаєма енергія, зовнішнє і внутрішнє тертя, метод контролю

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DEVELOPMENT OF A METHOD FOR ESTIMATING THE RESISTANCE OF FIBERS AND THREADS TO A SLIDING BEND BASED ON ENERGY CONSUMPTION FOR EXTERNAL AND INTERNAL FRICTION

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1. Introduction

Modern production of woven and knitted textiles requires the application of effective methods to predict the results of processing original raw materials and semi-finished products (fiber, yarn, and thread, hereafter referred to as thread). The result of production depends largely on conditions of interaction between a thread and the working bodies of machines. This is predetermined by the requirements related to the improvement of performance efficiency of textile production and the level of its automation.

There is a concept of the textile passability of threads [1], which is applied when assessing their capability to pass through the thread-guiding gear. The best passability is explained by the lower force resistance on the thread from the side of working bodies in processing machines. This follows from the results of research that addressed the interaction between a thread and the working bodies of textile machinery [2], specifically, during a spinning process [3], knitwear [4], and weaving [5]. In addition, a comprehensive assessment of the thread passability is specified when improving the methods to design the machines' working bodies [6] and when forecasting technological parameters [7].

However, predicting the character of the specified causal relationships and their consequences is difficult in actual practice and thus establishing effective methods to control and forecast conditions for the interaction between threads and machines' working bodies is a relevant task.

Given the diversity of textile raw materials and semi-finished products that are used in the manufacture of textiles, there is a need for more informative control methods. The basic requirements put forward to them is the need to not only account for the effects of manifestation of frictional interaction with the elements of machines' working bodies, but also to take into consideration the impact of changes in the internal structure during deformations [8–11]. Therefore, it is a key area of research and development to improve control systems based on enlarging the informativeness of their results.

2. Literature review and problem statement

An analysis of results of known studies into the character of behavior and force load on textile semi-finished products (fiber, yarn, thread) in the process of their obtaining and processing has led to the conclusion on that the dominant type of interaction of the stretched thread is its sliding bend relative to working bodies that have the rounded working edges [8]. Under conditions of the sliding bend, a stretched thread undergoes a set of deformations; the strains that form within it could lead to its destruction at critical values.

Studying the force load on a stretched thread in the process when it streamlines a cylindrical surface at a certain capture angle, dates to 1775 – the year when a research by L. Euler was conducted. The analytical dependence, derived by him, made it possible for the first time to assess the balance of stretching forces for the climbing T_0 and descending T branches of a thread that is in contact at capture angle β with a rough cylinder at sliding friction coefficient μ.

However, application efficiency of a given formula is rather limited due to the adopted assumptions: the thread is completely flexible, non-stretchable, and weightless. That does not make it possible to take into consideration the components of efforts related to the deformation of a thread when bending and stretching.

The subsequent development of theoretical bases for this interaction, as well as processes that are similar to it, took into consideration the patterns in the thread properties and structure, conditions for frictional interaction, force loading, parameters of the sliding surface, shape, and other factors.

The issues related to the static, kinematics, dynamics of the thread were also investigated [12]. The results of scientific research have, for example, identified the patterns in the influence of velocity V on a contouring (stationary) displacement of the thread. When it streamlines a cylindrical surface of diameter $2r$, the ratio of tension forces becomes different from (1) and takes form (2), and when calculating a normal reaction N to the thread from the cylinder – (3).

When it streamlines a cylindrical surface of diameter $2r$, the ratio of tension forces takes form (1), and when calculating a normal reaction N to the thread from the cylinder – (2).

$$T = T_0 e^{\mu\beta} - \mu V^2 (e^{\mu\beta} - 1), \tag{1}$$

where e is the base of natural logarithms.

$$N = \left(\frac{T_0}{\mu r} - \frac{V^2}{r} \right) e^{\mu\beta}. \tag{2}$$

It should be noted that interaction between materials, similar to the thread, during their deformation was examined not only when studying textile processes. Thus, for example, one of the first papers on a given subject reported a study into the stresses state of a cable that streamlines a cylindrical surface and that has bending rigidity [14]. Based on results, the authors established patterns in the formation of reactions and ratios of tension forces in the climbing and descending sections of the cable taking into consideration a decrease in the capture angle caused by bending rigidity.

The results obtained largely defined the patterns, generally accepted and existing at present, for the force interaction between a thread and the cylindrical elements that it streamlines, taking into consideration their diameter, bending rigidity of the thread and its tension. Specifically, a fundamental conclusion was the formation of concentrated reactions at points where the thread climbs and then descents to the streamlined surface. The existence of such reactions under actual conditions could lead to local deformations in a thread along the transverse direction, specifically at points where the contact with a cylindrical surface starts and ends.

The developed scientific basis for the examined process influenced the formation of a specialized field – the mechanics of threads, and greatly contributed to their implementation in terms of improving textile production. However, in order to increase their efficiency through automation and management, practical experience required a detailed knowledge when accounting for the properties of a processed textile semi-finished product (fibers, yarns, thread) that interacts with the machines' working bodies.

That led to an in-depth research into the influence of properties and structure of the thread on its strained state. This applies to its longitudinal and transverse deformations, relaxation characteristics, conditions for frictional interaction and force loading when moving at different speeds, as well as the parameters of the sliding surface and its shape.

Specifically, the models were obtained of the force interaction that takes a thread thickness into consideration [15], and consequently, its bending rigidity EI [16–19]. The studies revealed their significant influence on tensile force of the thread that streamlines a cylinder [13–15]:

$$T = T_0 e^{\mu\beta} - b(e^{\mu\beta} - 1), \tag{3}$$

where b is the parameter that depends on bending rigidity of the thread, its thickness, and radius of the cylinder.

The established influence of bending rigidity required development of the methods for determining this characteristic. Theoretical foundations were formed to define it [20–22], with the control variants proposed for practical application [23–27], some of which were recognized as inventions [28–30].

However, despite the progress made, created models have flaws linked to the limited accounting of the deformation characteristics of threads, features of their internal structure and changes in it under deformations. They affect the character of motion and the strained-deformed state of the thread. Therefore, adequate description of the implemented processes of mechanical processing of threads needed further refinement of methods to calculate strength parameters of the examined interaction.

The most important results were obtained when examining the conditions for thread deformation depending on the character of its motion and parameters of the streamlined surface. While exploring its displacement on the surface with large curvature, the differences were established in the force fields that accompany it, related to features of the internal structure [31, 32]. Scientists identified the non-linearity of thread deformation at stretching, predetermined by the thread viscoelasticity and plasticity at relative motion [33]. They proved the instability of a value for the friction coefficient in a contact area. They studied the shear phenomena resulting from the geometrical non-linearity [34]. For example, paper [32] proposed a differential equation for thread curvature 1/r, taking shear forces into consideration [34].

Summarizing the results obtained, one should note their fragmented character. That does not make it possible to comprehensively, with appropriate «linkage», to take into consideration the identified features in the thread deformation. The reason for this is the lack of commonality of theoretical approaches to solving the set problems.

Therefore, despite numerous searches, up to now there is no any effective model of interaction between the thread and a cylindrical surface that could predict to the required accuracy the forces of tension. It still is not possible to fully analytically take into consideration all patterns in the deformation, in the longitudinal and transverse directions, of the thread as an anisotropic material. Proof of this is the results of research [24], which established experimentally the influence of the thread structure, the length of the line of contact, and tension, on the thread bending rigidity. Special mention should be made of the thread creasing property that occurs in a contact area with the streamlined cylinder, causing a change in its thickness, the cross-sectional area, and the redistribution of pressure forces along the length of the contact. It is established that creasing property leads to the stress redistribution inside the cross-section of a thread [35] and changes its capture angle relative to the streamlined surface [36]. This affects the magnitude of resistance at displacement [37].

An important reason for the lack of effective mathematical models for force interaction between a moving thread and the machines' working bodies is a failure to account for the parameters of heterogeneity in its properties and structure.

According to [8], a crucial role in the examined interactions belongs to the thread heterogeneity, primarily in terms of its linear density. Under such conditions, parameters of the thread stressed-strained state are strongly dependent on the heterogeneity of its properties and structure. Along with this, the problem is complicated by influence of the machines' working bodies on the thread [38]. Therefore, a solution based on employing the models constructed on the principles of continuity does not necessarily yields correct results.

The task on modelling the examined processes becomes even more complex if we consider a thread that consist of individual structural elements having different properties and interconnected by forces of varying character [39]. Under such circumstances, one should take account of the defects in a material [40], predetermined by its micro- and macrostructure [41–44]. In this case, there is a need to refer to probabilistic representations and to the apparatus of theory of stochastic processes, inherent, for example, when examining composites [45, 46].

Thus, poor effectiveness of existing calculation models does not provide for the required accuracy in determining the forces of thread tension when it moves streamlining a cylindrical surface. That testifies to the expediency of solving a series of practical tasks by using experimental control methods, based on the simulation of actual conditions for interaction between a thread and the processing machines' working bodies. In contrast to standard test methods, one of the specified conditions is the employment of faster loading regimes, inherent to textile processes [47].

Summarizing the results of known studies that addresses the construction of mathematical models for the interactions of threads in the process of their sliding bend relative to the rounded surface of the processing machines' working bodies edges, one should note the reduced effectiveness of the constructed estimation models that do not ensure the required accuracy when determining the forces of tension. It is therefore advisable to apply, when dealing with a number of practical tasks, the experimental control methods.

3. The aim and objectives of the study

The aim of this study is to improve the informativeness of control over a force load on the thread at its sliding bend relative to a cylindrical surface under conditions of a comprehensive manifestation of properties and structural features of the thread.

To achieve the set aim, the following tasks have been solved:

– to substantiate test parameters, control over which would enable the integrated accounting of the physical-mechanical properties and structural features of the thread that manifest themselves at its sliding bend;

– to investigate the conditions that ensure the identification of parameters associated with the manifestation of the internal and external friction at a sliding bend;

– to devise a technological scheme of tests and to conduct comparative tests using threads made from different materials of varying structure.

4. Materials and methods to study an instrumental technique for estimating the thread resistance to a sliding bend

When substantiating the variants for such a control, we considered the need for conducting a test under conditions of the thread tension and displacement when its friction and physical-mechanical properties manifest themselves, as well as its structural features. In order to simulate actual conditions for the frictional interaction, a radius of rounding the edges of working bodies should be commensurate with the thread thickness. In this case, there may occur a manifestation of not only external, but also internal, contact friction, predetermined by the above-specified effects that lead to the deplanation of the thread cross-section. This is consistent with generally accepted theoretical provisions on the manifestation of materials bending deformation [34], as well as features of bending the thread-like bodies at enhanced curvature [14, 31, 48]. Specifically, papers [2, 48] show that under such circumstances the energy dissipates at bending.

Its magnitude for threads of different structure can vary from zero and above. An increase in the irrevocably dissipated energy will lead to a change in power parameters of the thread when it streamlines a cylindrical surface.

Therefore, the energy consumed can be chosen as an overall assessment of structural, deformational, and frictional characteristics of the thread, affecting its resistance to a sliding bend. If the magnitude of a thread displacement is constant, the overall assessment could be the work performed (all other structural and operational parameters being equal) by the tension force of the descending branch of a thread that streamlines a cylindrical surface at certain curvature. However, in this case, it is advisable to identify the share of energy required to overcome the external friction.

To account for this share of energy, we employed results from analysis [14], which explored the correlation between forces of tension in the climbing T_0 and descending T sections of cable 1, which streamlines at capture angle β cylindrical surface 2 of radius r (Fig. 1, where β=π rad.). Authors identified a possible reduction in capture angle $\beta=\alpha+(\lambda_1+\lambda_2)$ due to the thread's bending rigidity EI. The magnitude of reduction is the sum of angles λ_1 and λ_2.

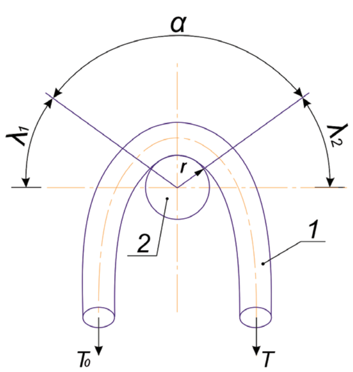

Fig. 1. The bend-elastic thread streamlines the thread-guide contour of cylindrical shape

The result is the derived analytical expression for sum $(\lambda_1+\lambda_2)$, which takes the following form:

$$(\lambda_1+\lambda_2)=\left[\arccos\left(\frac{e^{\mu\beta}(k^2-1)}{1+e^{\mu\beta}(k^2-1)}\right)+\arccos\left(1-\frac{1}{k^2}\right)\right], \quad (4)$$

where

$$k^2=\frac{2T(r)^2}{El};$$

μ is a friction coefficient.

Expression (4) allows us to argue about the dominant influence of the radius of cylindrical surface r on a change in the capture angle (due to the presence of bending rigidity). A decrease in the radius forms the conditions for a more contrast impact of EI on the magnitude of the actual capture angle $\alpha=\beta-(\lambda_1+\lambda_2)$ and, therefore, on the ratio T to T_0. Such a conclusion is possible assuming that the thread friction coefficient along the cylinder surface μ=const. The specified relation T to T_0 is proposed to determine taking into consideration the following dependence:

$$T=T_0\left[\frac{1}{k^2}+e^{\mu\beta}\left(1-\frac{1}{k^2}\right)\right]. \quad (5)$$

Analysis (5) reveals a comprehensive effect on the magnitude of thread tension exerted by its bending rigidity, tension, and the radius of a streamlined cylinder. For example, at constant β and μ, a decrease in magnitude $k^2=2T(r)^2/EI$ may lead to a 50 % decrease in the actual capture angle α, causing respective changes in ratio T/T_0.

At the same time, at magnitude $k^2>1.500$, the value for α does not exceed 5°, 0.085 rad., that is, a change in the capture angle will stay within a statistically valid error. Under such conditions, in order to identify intervals of values for tension forces and the radius of a streamlined cylindrical surface, we derived a graphical dependence $k^2=f(T; r)$, shown in Fig. 2. It was constructed at $EI=0.066$ N·mm^2 (the value is taken from [25] when testing a linen yarn 50 tex, using method [26], applying (4)).

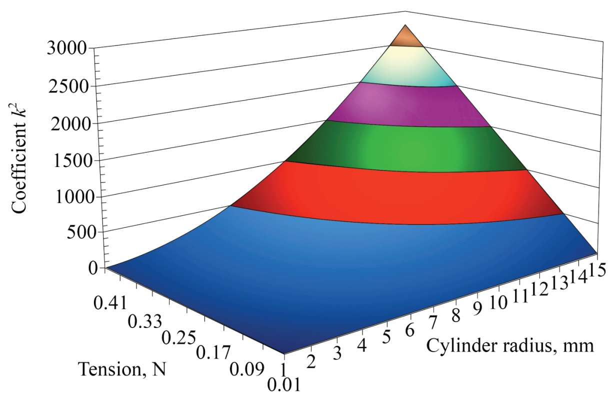

Fig. 2. Dependence of parameter k^2 on tension of the climbing end of a thread and radius of the streamlined cylinder

An analysis of the derived dependence (Fig. 2) allows us to conclude that the specified intervals of k^2 values are formed when using the radius of a streamlined cylindrical surface larger than 10 mm and tensions higher than 0.2 N.

The results obtained in relation to the developed control method make it possible to identify the conditions under which the interaction of a rigid thread when streamlining a cylinder would not differ from the character of the force load on the absolutely flexible one. Note that in order to minimize the conditions for manifestation of the thread creasing property in the contact area, there is an obvious need for its minimally possible tension. In this case, the performed work $A_{ext.fr}$ will be defined by the external friction only.

A change in the character of interaction between a thread and a cylindrical surface under condition $k^2>1{,}500$ will lead to the formation of additional work due to the forces of internal friction $A_{intern.fr.}$, while the total work A will be equal to the sum of $A_{intern.fr}$ and $A_{ext.fr}$. Given such a variant of testing, it is possible to identify the share of work caused by internal friction, for example in the form of an estimate of the manifestation of internal friction D, determined from formula $D=(A-A_{ext.fr})/A$. $D=[(A-A_{ext.fr})/A]\cdot 100$, %. Hence it follows that a mechanical test, simulating the process of a sliding bend, should be carried out under conditions for forming different k^2 values. This, according to the findings with respect to the analysis of graph in Fig. 2, is possible when using cylindrical surfaces of different radius.

Given the above, the basis for a new instrumental control method for the evaluation of the thread resistance to a sliding bend could be a scheme similar to [48]. The principal difference will be a possibility to displace the thread, stretched with a bend, in order to control the work, carried out at the same time, caused by the external and internal friction. To derive an estimate for D, tests should be carried out in two stages, at each of which a thread, stretched by a constant force T_0, should streamline cylindrical surfaces with a different radius of their curvature at a constant capture angle β.

According to it, the thread streamlines a cantilevered round rod. The free end is stretched by constant force T_0, while the descending section is fixed in the clamp at a thread displacement unit; the energy consumed is calculated using a computer.

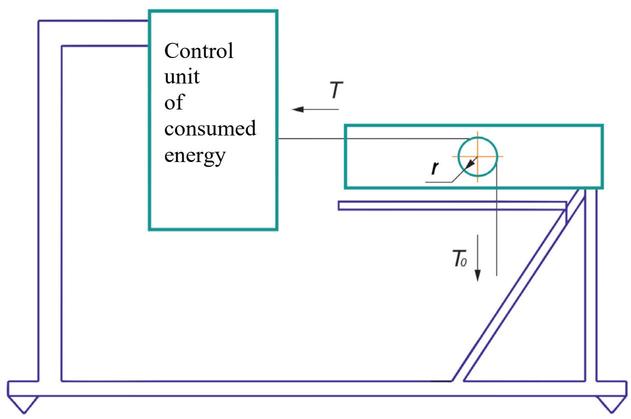

Fig. 3. Schematic of testing a thread in order to estimate resistance against a sliding bend

At the first stage of testing, a moving thread streamlines a cylinder with a curvature radius r_1=15 mm (to satisfy condition $k^2>1.500$). In this case, we estimate the work required to overcome only the external friction forces. At the second stage, we use of cylinder with a smaller radius r_2=0.5 mm$\ll r_1$ to create conditions at which $k^2\leq 1.500$. Such test will ensure a simultaneous manifestation of the external and internal friction. Upon completion of each stage of the test, we determine the magnitude of the energy consumed per a sliding bend. The outcome of this test is the estimates for: A, $A_{ext.fr}$ and D, which make it possible to determine the thread resistance to a sliding bend.

5. Results of studying the feasibility of applying a new instrumental technique for estimating the thread resistance to a sliding bend

We fabricated a prototype device based on the developed scheme. By using it, we performed tests of threads and yarn, different in properties and structure: basalt thread (250 and 500 tex), carbon thread (100 and 200 tex), linen yarn (46 and 80 tex), polyester thread (30 and 60 tex). A sliding bend at a constant magnitude of the thread displacement (100 mm) was enabled relative to the steel cylindrical rods with a length of 15 mm and radius r_2=0.5 and r_1=15.0 mm. The thread capture angle was the same: 2.36 rad. Initial tension T_0=0.618 N.

When testing, we determined energy A_i (mJ) consumed for the displacement of samples made from various materials, different in thickness, applying the streamlined cylinders of different radii. The results are shown in the form of a chart in Fig. 4.

It shows different variants that satisfy the following conditions:

– a carbon thread (twist factor: for linear density 100 tex – 1,000; for linear density 200 tex – 1,400) (variants 1–4): 1 – r_1=15 mm, 100 tex; 2 – r_1=15 mm, 200 tex; 3 – r_2==0.5 mm, 100 tex; 4 – r_2=0.5 mm, 200 tex;

– linen yarn (twist factor: for linear density 46 tex – 3,200; for linear density 80 tex – 3,000) (variants 5–8): 5 – r_1=15 mm, 46 tex; 6 – r_1=15 mm, 80 tex; 7 – r_2=0.5 mm, 46 tex; 8 – r_2=0.5 mm, 80 tex;

– a basalt thread (twist factor: for linear density 250 tex – 800; for linear density 500 tex – 1,800) (variants 9–12): 9 – r_1=15 mm, 250 tex; 10 – r_1=15 mm, 500 tex; 11 – r_2=0.5 mm, 250 tex; 12 – r_2=0.5 mm, 500 tex;

– a polyester thread (twist factor: for linear density 30 tex – 3.300; for linear density 60 tex – 3,100) (variants 13–16): 13 – r_1=15 mm, 30 tex; 14 – r_1=15 mm, 60 tex; 15 – r_2=0.5 mm, 30 tex; 16 – r_2=0.5 mm, 60 tex.

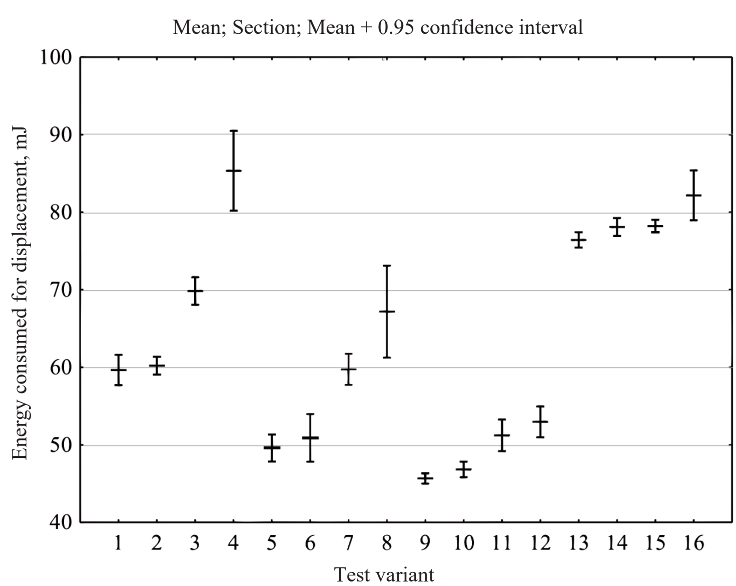

Fig. 4. Change in the energy consumed to displace the tested samples based on test variants (1...16)

The results shown in Fig. 4 allow us to draw a conclusion about the possibility to differentiate the examined threads and yarn based on the degree of their resistance to a sliding bend, including the condition for a manifestation of external friction only. For example, the lowest energy required to overcome the external (frictional) friction is demonstrated by a basalt thread. The highest magnitude of energy under these conditions is characteristic of polyester threads.

Evaluation of resistance to a sliding bend (the overall consumed energy) is carried out when testing a carbon thread and linen yarn. In this case, an increase in linear density leads to a higher estimate obtained for all variants in comparison with similar examples, but of less linear density.

6. Discussion of results of studying the new technique to control parameters of the thread interaction at its sliding bend

An analysis of results shown in Fig. 4 reveals, first and foremost, that there is a possibility to compare the forces of external friction among the tested samples. A pairwise analysis of the work used to overcome them (variants 1–2, 5–6, 9–10, 11–12) demonstrates the absence of statistically significant differences in $A_{ext.\ fr}$ for the identical materials with different thickness. That confirms that when streamlining a cylinder with a small curvature, the threads do not reveal irreversible energy losses at the emerging set of deformations. Energy is spent solely to overcome the forces of external friction. The lowest friction force occurs when using a basalt thread (≈ 48 mJ), and the largest – a polyester thread (≈ 78 mJ). The data acquired allows us to estimate differences in friction coefficients *f*. The lowest was demonstrated by a basalt thread, followed by linen yarn, a carbon thread, and a polyester thread.

Along with the identified ratios of external friction forces, of special interest are the values for energy consumed to displace a thread when it streamlined the rods of elevated curvature. In this case, one observes a manifestation of the overall impact from the external and internal friction. It is noteworthy that the largest work is required for threads of elevated thickness (linear density). For almost all variants of tests, the energy required to displace such threads relative to cylinders with a small radius is significantly higher.

In order to assess the degree of manifestation of the internal friction, we employed the magnitude *D*. Values for the estimates of *D* (based on test variants) are shown in the form of a chart in Fig. 5.

The data from a chart (Fig. 5) indicate that the largest share of energy to overcome internal friction is generated by a carbon thread (D=18.2 %) and by linen yarn (D=11.1 %) with elevated linear density. The lowest value of *D* characterizes a polyester thread. For all variants, threads with less thickness demonstrate the lower value for estimate *D* than that for the thicker identical threads. The identified differentiation in the values for *D*, for example, in the case of linen yarn and polyester threads, can be explained by differences in changes in the internal structure of threads at their bending. While ensuring the conditions for a bend, similar to actual loads during processing, a displaced thread undergoes a set of deformations that cause changes in its internal structure and a corresponding loss of energy. Note that accounting for the specified features at deformation by using existing estimation models is not possible at present, especially when using threads with enhanced heterogeneity in structure and properties. Therefore, in order to obtain reliable data on the differences between the compared threads, in terms of evaluation of their passability relative to the machines' thread-guiding gear, the proposed experimental method of analysis is more efficient.

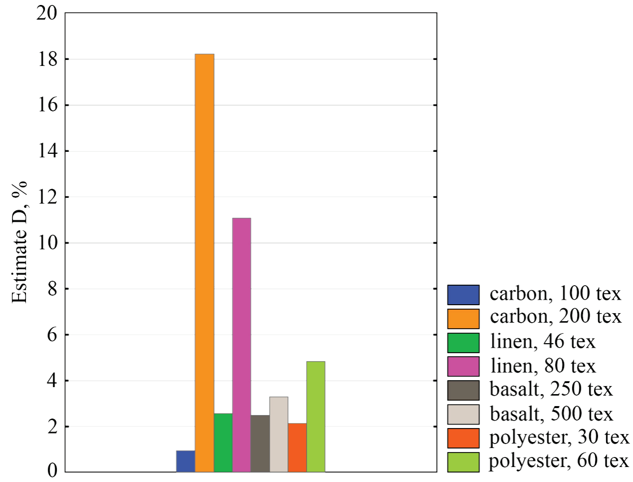

Fig 5. Values for the estimate of manifestation of internal friction *D* for the tested samples of textile semi-finished products made from different materials and of different thicknesses

Therefore, when analyzing threads based on the energy consumed for displacement relative to cylindrical surfaces, it is possible to differentiate the properties of threads based on the degree of their sliding bend. This is provided by the ratio of energies required to overcome the forces of external and internal friction. A given ratio is proposed as an estimate of the resistance to a sliding bend. It is determined in the course of the above-described two-stage tests based on the proposed scheme of interaction between a thread and a cylindrical surface and by registering the consumed energy.

When implementing the proposed method in practice, it is required at both stages of testing to ensure the similarity of materials that the cylinders are made from, and which the threads streamline, as well as the machining quality of their surfaces. Thread tension forces, when testing in order to estimate external friction, should be the smallest, providing for the absence of thread creasing when in contact with a cylinder of lowered curvature. At the second stage of testing, the starting forces of tension and the thread displacement speed must conform to the actual conditions and loads in thread processing. However, in order to ensure comparability, their magnitudes in relation to all the tested threads should not.

We should note the appropriateness of accounting for the variability in estimate *D* along the length of the tested sample. The importance of this is due to the uneven thickness and structure of threads along their length. This is especially true for the reinforced and pile threads (yarn), which are characterized by displacements of the structural elements along the length and by the formation of geometrical nonlinearity. If this information is available, it is possible to estimate the variation in internal friction and, consequently, the varying additional component of force loads. That would make it possible to predict the course of technological processes in textile machines. This constitutes the further advancement of the proposed test method. However, its implementation requires solving a series of technical tasks related to determining the energy consumed, along the individual elements of length of the tested sample.

7. Conclusions

1. Existing estimation models of interaction between threads and machines' working bodies during their processing do not provide for the required accuracy when determining the force characteristics underlying the concept of thread passability. It is advisable to employ experimental testing methods based on the simulation of actual conditions for processing, specifically, by a thread's sliding bend relative to a cylindrical surface.

2. In order to estimate the resistance of thread, dependent on the totality of its properties and deformation features in a contact area, we have proposed the total energy A that is consumed for displacement at a sliding bend. To account for the cumulative effect exerted on A by the external and internal friction, the sliding bend of the thread, of rigidity EI and a force of tension T, should be performed relative to a cylindrical surface of radius r_2, commensurate with the thread's thickness. In order to identify the energy consumed by external friction $A_{ext.fr}$, a condition $2T(r)^2/EI \geq 1500$ must be satisfied. When EI and T are constant, this is observed at $r_2 \ll r_1$.

3. The scheme of testing the thread resistance to a sliding bend involves two stages: applying r_2 and r_1. At each stage we determine: total energy A, energy that is dependent on the manifestation of external friction $A_{ext.fr}$, as well as the proportion of energy from internal friction in the form of an estimate $D=[(A-A_{ext.fr})/A]\cdot 100$, %. Verification of the new method using threads and yarns from different materials and of varying structure has confirmed the possibility to differentiate them based on their capability to resist a sliding bend under different conditions of interaction with a cylindrical surface.

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