PREVENTION OF THE FLAMMABILITY OF RAW COTTON WITH THE USE OF COMPOSITE POLYMER COATINGS IN FRICTION UNITS

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Abstract - The physicomechanical properties of the composition of thermoplastic polymers have been studied in the example of polyethylene and polypropylene with various fillers. Based on the determination of the effect of the spark temperature on the ignition of cotton fiber arising during interaction with structural materials, compositions of thermoplastic polymer materials for friction units of cotton machines and mechanisms have been developed, which eliminates the possibility of ignition and spark formation when interacting with raw cotton.

Keywords: Raw cotton, Cotton processing machines and mechanisms, Ignition and ignition of cotton fiber, Self-ignition temperature of cotton, Composite polymer material, Tribo-thermoelectric.

1. Introduction

The friction of structural materials interacting with raw cotton is characterized by the variety and complexity of simultaneously occurring processes on the contacting surfaces [1]. Especially as a result of changes in technological conditions in the contact zone, in some cases, there may be opportunities for raw cotton to catch fire when it collides with solid and heavy impurities, as well as due to the occurrence of static electricity in the contact zone in a cotton-metal pair, which simultaneously leads to an increase in the coefficient of friction and temperature when interacting with raw cotton [2, 3].

In practice, cotton gins and cotton harvesting points occur in the event of fires of raw cotton from a smoldering slice or fly of cotton, which ignites due to excess temperature and accumulation of electrification in the contact zone when the cotton fiber is rubbed with a metal surface [4]. Especially for the self-ignition of cotton, unfavorable conditions are created when cotton fibers are wound on the surface of the pegs of the working bodies of mechanization tools, where a zone of elevated temperature occurs in the contact points under friction conditions. During prolonged exposure to high temperatures on cotton fiber, it self-ignites, giving rise to fire [4].

Usually, fires in raw cotton zones are protracted and difficult to extinguish, which requires a lot of effort and money. When laying raw cotton in riots, during the intensive period of cotton harvesting, to ensure the safety of cotton during storage from spoilage and disassembly of cotton riots, as well as when digging tunnels in raw material zones, various machines and mechanisms with identical scooping elements made in the form of pegs of various design designs are used [5].

Recently, polymer materials and composite coatings based on them have been increasingly used for the manufacture of parts of cotton gins and cotton processing machines and mechanisms interacting with raw cotton and cotton fiber [6]. Especially parts made of thermoplastic polymer composite materials become an integral part of the working bodies of various machines and mechanisms, providing the necessary physicomechanical and physicochemical properties in the friction zone of the contacting surfaces paired with a fibrous mass [7].

In this regard, special attention is paid to the creation of new, effective, and modified composite polymer materials and coatings based on their interaction with raw cotton, which, along with high antifriction-wear-resistant and physicomechanical properties, also have the best electro-thermal characteristics [8].

2. Materials and Methods

Compositions based on polyethylene with a density of 0.954 g/cm^3 grade I-0754 (ShGXK) and compositions based on polypropylene with a density of 0.92-0.93 g/cm^3 grade J-150 (UGXK) processed by injection molding according to the technological regulations were obtained as the sample material for the study [9].

Carbon graphite fillers were selected as additives, and the above mineral and fibrous fillers, such as talc, carbon black, graphite, kaolin, wollastonite, chalk, fiberglass, and cotton lint were also used [10].

Standard samples such as blades, plates, and discs made of compositions of thermoplastic polymers with various fillers were made on a PL-71 injection molding machine.

The bending strength of the polymer composition was determined following GOST 4648-78 on samples with dimensions of 55x6x4 mm on the device U34-10 TM. The speed of the relative movement of the tip was 10 mm/min [11].

The impact strength was determined according to GOST 4647-80 on pendulum copra, on samples of a prismatic rectangular cross-section with a size of 50x6x4 mm.

The determination of the elastic modulus during bending was carried out on a test machine of the UM-5 type following GOST 9550-81 and on samples with dimensions of 55x6x4 mm.

Determination of Brinell hardness was carried out on samples representing a bar with a thickness of at least 5 mm and a width of at least 15 mm. During the test (GOST 4670-77), a steel ball with a diameter of 5 mm under a force of 50 N was pressed into the material sample for 60 seconds, then the depth of the ball indentation was measured using an indicator [12,13].

Triboteploelectric properties were evaluated on a disk tribometer to determine the coefficient of friction, static charge density, and temperature in the contact zone of composite polymer materials during their interaction with raw cotton, allowing to determine the coefficient of friction in the range of 0.1-0.4, the density of the electrostatic charge $0{,}93\text{-}2{,}37 \cdot 10^{-6}$ Kl and temperatures in the range of 273-350 K [14].

Raw cotton with the following specific properties and composition was chosen as the counter-body of rubbing pairs: cellulose 90-91%, pentazane 1.5-2.0%, pectin substances 2%, protein 1.5-2.0%, fats and wax 0.5-1.0%, lignin 2-3% [15].

The temperature in the friction zone was measured using a DS18B20 sensor, the principle of operation of which is based on a change in EMF depending on temperature. The cold junction of the thermocouple was in the thermostat at 273 K [16].

The resulting charges in the friction zone were removed using electrodes. The value of the static electricity charge was determined by measuring the value of the potential using the 2N3819 sensor [17].

3. Results and Discussion

Most of the machines and mechanisms used in the collection, preparation, storage, and processing of cotton consume a significant amount of energy, have insufficient productivity, cause damage to the fiber and cotton seeds, as well as burning the fiber [18]. Especially machines and mechanisms that play a crucial role in ensuring timely and high-quality processing of raw cotton to meet the growing need for quality and preservation of the natural properties of cotton fiber need further improvement to increase their efficiency, for which it is necessary to study the specific conditions of individual nodes of working bodies interacting with cotton [19].

One of the main causes of cotton fires is sparks arising from the impact of metal pegs of working bodies on solid inclusions present in cotton. Raw cotton contains 0.1-0.2% heavy impurities (by weight) of various sizes that can cause a fire [20].

A spark is a piece of metal or stone that is incandescent to glow. The dimensions of the impact and friction sparks depend on the fragility of the material of the colliding bodies, and the impact force and usually do not exceed 0.1-0.5 mm in diameter. An increase in the temperature of a heated particle of stone or metal to glow also contributes to its oxidation by oxygen of the surrounding air [21].

Studies of the dependence of the temperature of the impact spark and friction on the material of the colliding bodies and the impact force are widely covered in the work. According to these studies, when an abrasive stone particle with a linear velocity of over 5.0 m/s hits a metal visor made of steel, a spark temperature of over 1550 °C occurs at a specific load of $P < 0.6$ MPa, and the spark temperature increases linearly with increasing load and linear velocity. With the further movement of the spark of impact and friction, it cools and gives off a relatively small amount of heat to the surrounding space, due to its small mass [22].

If we consider a spark of maximum dimensions, then the amount of heat q given off by this spark when it cools from the initial maximum temperature t_H to the self-ignition temperature of cotton t_{CB} can be determined by the following expression:

$$dq = V \cdot \gamma \cdot C_t \cdot dt \qquad (1)$$

or after integration:

$$q = \int_{t_{св}}^{t_н} V \cdot \gamma \cdot C_t \cdot dt = V \cdot \gamma \cdot C_t \cdot (t_н - t_{св}) \qquad (2)$$

where, V - the volume of a spark (a red-hot particle of a stone or metal of a spherical shape);

γ - specific gravity of spark material;

C_t - specific heat capacity of the spark material (at average temperature);

t_H - initial maximum spark temperature;

t_{CB} - the self-ignition temperature of cotton fiber when a spark enters it.

A 0.5 mm diameter steel spark, cooling from the initial temperature t_H = 1500 °C to the self-ignition temperature of cotton fiber t_{CB} = 165-200 °C at a humidity of 10-12% cotton fiber, gives off less than 0.06 Kal of heat.

The time of free flight of a spark without contact with cotton is calculated in tenths and even hundredths of a second. In this case, it is of practical interest to investigate and identify the pattern of changes in the temperature of the spark during its flight [23].

A certain period corresponds to a certain temperature of the spark for a certain period and the total duration of cooling of the spark τ from t_H to t_{CB} of the cotton fiber in which it falls. The spark temperature for each time interval and the total duration of the spark cooling τ to t_{CB} is determined by calculation based on the dependence of heat transfer from a spherical body into an unlimited space [24].

Denoting by θ - the dimensionless ratio of the difference between the initial and self-ignition temperature to the difference between the initial temperature and the air temperature, we write:

$$\theta = \frac{(t_н - t_{св})}{(t_н - t_в)} \tag{3}$$

where, t_B – air temperature,°C.

Let's assume that the air temperature does not change during the period under consideration (t_B = const), the spark cooling occurs uniformly ($V_{cooling}$ = const). In this case, the following dependence is valid:

$$\theta = f(B_i; F_o) \tag{4}$$

where, B_i - the bio criterion equal to:

$$B_i = \frac{\alpha \cdot d}{\lambda_p}, \tag{5}$$

where, F_o - the Fourier criterion equal to:

$$F_o = \frac{\alpha \cdot \tau}{d^2} = \frac{\tau \cdot \lambda_p}{d^2 \cdot C_p \cdot \gamma_p} \tag{6}$$

where, α - heat transfer coefficient between spark and cotton fiber;

d - spark diameter;

λ_p - thermal conductivity coefficient of the spark material;

a - the coefficient of thermal conductivity of the spark material;

C_p - specific heat capacity of the spark material;

γ_p - specific gravity of spark material.

With known values of the Fourier criterion F_o, the duration of cooling of the spark from t_H to t_{CB} is determined:

$$\tau = \frac{F_o}{\lambda_p} \cdot d^2 \cdot C_p \cdot \gamma_p \tag{7}$$

However, the analytical solution to the problems of dependence research $\theta = f(Bi; F_o)$ is associated with significant difficulties.

For practical purposes, a graphoanalytic method is used to determine the value of the Fourier criterion from the corresponding nomograms for known values of θ and the B_i criterion [25].

To determine the values of the B_i criterion, it is necessary to calculate the heat transfer coefficient α. The heat exchange between spherical particles and the air medium at a value of $R_e < 620$ is expressed by the following criteria dependence:

$$St \cdot \mathrm{Pr}^{0,67} = 2{,}63\mathrm{Re}^{-0,5} \tag{8}$$

where, St - Stanton's criterion;

Pr - Prandtl's criterion;

Re - The Reynolds criterion.

The Stanton criterion, in turn, can be expressed through the criterion of Nusselt, Prandtl, and Reynolds:

$$St = \frac{Nu}{\mathrm{Pr} \cdot \mathrm{Re}} \tag{9}$$

Substituting the value of the Stanton criterion into expression (8) and after the corresponding transformations, the Nusselt criterion is determined:

$$Nu = 2{,}63\mathrm{Re}^{\frac{1}{2}} \cdot \mathrm{Pr}^{\frac{1}{3}} \tag{10}$$

The physical parameters for determining the heat transfer coefficient between a spark and cotton are taken for clean air at the self-ignition temperature of a cotton fiber [26]. With known values of t_{CB} and d, it is possible to determine the heat transfer coefficient between a spark and a cotton fiber by the formula:

$$\alpha = 0{,}165\sqrt{v}, \ \frac{kkal}{m^2 \cdot s \cdot grad.} \tag{11}$$

where, v - the speed of movement of the spark, m/s.

The speed of movement of the spark is assumed to be equal to the speed of free movement of the body at the moment of impact or the linear velocity of the rotating body for the point of origin of the spark.

This technique can be used to determine the temperature of a spark t_H at any time after its formation [27].

However, the ignition of cotton fiber from a spark of impact and friction is possible only with small values of the minimum ignition energy and small induction periods. Therefore, to determine the fire hazard of impact sparks and friction for cotton fiber, it is necessary to conduct appropriate studies [28].

The general sequence of actions when solving this kind of task is visible in the following example.

Example. Determine the duration of the action of sparks as a source of ignition, if it is known that they are formed upon the impact of a rod made of steel grade St.30 about a spike moving at a speed of 2.2 m/s in an air environment with an air temperature of 20 °C. The spark temperature is 800-1100 °C, and its diameter is 0.5 mm. The self-ignition temperature of raw cotton is 413 °C.

Solution. To determine the duration of cooling of sparks, we use the formula (4) $\theta = f(B_i; F_o)$.

1. The desired temperature ratio is calculated by the formula (3):

$$\theta = \frac{(t_н - t_{св})}{(t_н - t_в)} = \frac{900 - 413}{900 - 20} = 0{,}55$$

2. The heat transfer coefficient is determined by the speed of the spark flight:

$$\alpha = 0{,}165\sqrt{v} = 0{,}165\sqrt{2{,}2} = 0{,}245, \ \frac{kkal}{m^2 \cdot s \cdot grad.}$$

3. Using the formula (5), we determine the number of Bio:

$$B_i = \frac{\alpha \cdot d}{\lambda_П} = (\frac{0{,}245 \cdot 5 \cdot 10^{-4}}{25}) \cdot 3600 = 0{,}018$$

where, $\lambda_P = 25{,}0 \ \frac{kkal}{m \cdot h \cdot grad.}$ at $t_{CB=}$ 413 °C.

4. By the value θ and Bi, using the nomogram, we find the value of the Fourier number at θ= 0.55 and B_i = 0.18 the number F_o = 12.0

5. By the formula (7) we find the duration of cooling of the spark

$$\tau = \frac{F_o}{\lambda_P} \cdot d^2 \cdot C_P \cdot \gamma_P = \frac{12}{25} \cdot 3600 \cdot 5^2 \cdot 10^{-8} \cdot 0{,}136 \cdot 7700$$
$$= 0{,}450 \ s$$

where, C_P = 0,136, kkal/(kg·grad) at temperature of 413 °C.

Comparison of the values of the ignition temperature of cotton fiber (513 °C) and raw cotton (210 °C) with the temperature of the cut sparks (800-1100 °C), that the temperature of the sparks significantly exceeds the ignition temperature of cotton fiber and raw cotton, as a result of which the ignition of raw cotton from sparks can occur at procurement points and cotton gins [29].

In addition to the formation of a significant number of sparks, the formation of coils of cotton fiber is observed on the metal working bodies of machines and mechanisms, which are also a potential source of possible ignition of raw cotton due to its friction on the surface of the working bodies [30].

Therefore, to reduce the number of cotton fires, it is advisable to find such economical materials for the working bodies of machines and mechanisms that would preserve the natural properties of fiber and seeds, and exclude the possibility of sparking. Such materials having sufficient strength and operational reliability can be polymer composite materials or their substitutes [31].

Static electricity charges formed during the interaction of polymer materials with raw cotton contribute to the ignition of fibers, which, in turn, negatively affects the strength and spinning-technological properties of cotton fiber. In addition, the high electrification of polymer materials enhances the electrophysical, and physicomechanical processes in the friction zone and worsens their antifriction properties, as well as reduces the efficiency and effectiveness of the polymer materials used interacting with raw cotton. Taking into account the effect of electrification on the operational properties of polymer materials will significantly increase the efficiency of their use in machines and mechanisms of the cotton cleaning industry [32].

During the frictional interaction of polymer materials with cotton in the contact zone, triboelectric charges are formed and accumulated in the energy zone, which leads to an increase in the tension in the double electric layer in the contact zone, as a result of which the electrical component of the friction force increases, and the temperature increases, causing secondary thermal phenomena [33].

When polymer-cotton polymer materials are rubbed, static electricity charges are formed, which, depending on the sliding speed and pressure in the friction zone, increase and is in the range of 12-42·10^{-7} Kl [34].

To study the tribo-thermoelectric characteristics, which are factors for the occurrence of cotton fiber ignition, composite polymer coatings on steel 20 of various compositions of antifriction polyethylene compositions (APEC), as well as antifriction polypropylene compositions (APPC), providing the necessary physical and mechanical properties when working under conditions of interaction with raw cotton, were taken as a counter body [35].

Among other materials, polyethylene and polypropylene are widely used as an antifriction structural material, which are characterized by exceptional water resistance, high strength, good toughness, and resistance to aging and abrasion, for example, the relative wear resistance of polypropylene is 0.0115 m^2/cm^2 [36].

Table 1 shows the basic physical and mechanical properties of the most common and selected structural and polymer materials for the determination of tribo-thermoelectric properties. The compositions of antifriction composite polymer materials are given in Table 1.

Table 1. Formulation and composition of antifriction compositions based on polyethylene and polypropylene

Components	Antifriction polymer compositions based on polypropylene and polyethylene			
	APEK-1	APEK-2	APPC-1	APPC-2
Polypropylene (PP)	-	-	100	100
Polyethylene (HDPE)	100	100	-	-
Wollastonite	-	-	10	20
Graphite	-	5	-	5
Kaolin	-	10	-	10
Cotton Lint	10		-	-
Fiberglass	-	15	-	-
Soot	5	-	5	-
Talcum powder	5	-	5	-

The choice of types of fillers for the study is due to the following considerations (Table 1):

- graphite and soot improve the thermal and electrophysical properties of the composition;
- fiberglass and cotton lint give the material high strength and increase its resistance to thermomechanical influences due to reinforcement;
- talc, kaolin, chalk, and wollastonite are selected to reduce the cost of the recommended composite polymer materials.

In addition, the choice of these fillers is related to their availability and significant cheapness compared to other fillers [37].

These fillers differed in structure (particle shape) and particle size.

Carbon black was used as a granular filler, and graphite, kaolin, talc, and wollastonite were used from lamellar and flake fillers; fibrous fillers - fiberglass, and cotton lint were also used. The average sizes of filler particles ranged from 5.0 to 50.0 mkm [38].

The physical and mechanical properties of thermoplastic polymers change after the introduction of fillers into their composition. At the same time, the introduced fillers improve all the properties of polypropylene (PP), and the addition of cotton lint and fiberglass increases the bending fracture and hardness of the composition of polyethylene (HDPE), only the impact strength of HDPE decreases (Table 2).

Table 2. Physico-mechanical properties of antifriction compositions based on thermoplastic polymers

Indicators of physical and mechanical properties of the composition	Antifriction-wear-resistant compositions based on polypropylene and high-density polyethylene					
	HDPE	APEK-1	APEK-2	PP	APPK-1	APPK-2
Bending failure, σ_b, MPa	19	33,4	35,5	41	85,7	88,4
Impact strength, *a*, kDj/m^2	30	17,5	21,3	27	91,3	94,2
Brinell hardness, MPa	45	55,1	58,4	70	76,2	78,9
Flexural modulus of elasticity, E_b, GPa	0,65	0,62	0,65	1,6	1,75	1,80

The properties of compositions filled with mechanically activated additives are largely determined by the bond strength of the polymer with filler particles, the conformation and packing density of polymer macromolecules in the absorption layer, the nature of which is changed by mechanical activation of fillers, simultaneously combining mechanical and chemical effects. During mechanical activation of components, the change in properties is due to the production of highly dispersed particles with increased specific surface area and surface energy, as well as the formation of structural defects in solids and an increase in specific surface activity. Surface changes are manifested in the creation of active point centers that contribute to an increase in the sorption capacity of a surface unit [39].

Modification of polypropylene and polyethylene compositions shows that when using mechanically activated mineral fillers - talc, kaolin, wollastonite, graphite, and soot, which have a developed specific surface area and adsorption properties, interfacial interactions with the polymer increase, leading to an improvement in the complex properties of polyethylene compositions (APEC) and polypropylene compositions (APPC) [40].

However, the ignition of cotton fiber from a spark of impact and friction is possible only with small values of the minimum ignition energy and small induction periods. Therefore, to determine the fire hazard of impact sparks and friction for cotton fiber, it is necessary to conduct appropriate studies [41].

The range of contact pressures of the main working bodies of screw conveyors (conveyors), distributors, and cleaners, as well as kolkov machines working in contact with raw cotton and cotton fiber, are in the range of 0.001-0.05 MPa, the sliding speed in the friction zone ranges from 1 to 6 m /s. Based on this, the tribo-thermoelectric properties of the proposed compositions based on thermoplastic polymers were studied within the given limits of the operating conditions of the machines [42].

Triboteploelectric properties of compositions based on thermoplastic polymers in friction with raw cotton, depending on the pressure in the friction zone at a sliding speed of V = 2.0 m/s are given in Table 3, and depending on the sliding speed are given in Table 4 [43].

Analyzing the data in Table 3, it can be concluded that for compositions based on polyethylene APEC-1 and APEC-2, at constant sliding speeds, there is a change in the coefficient of friction with an increase in the load in contact, at the same time, compared with compositions based on polypropylene, APPK-1, and APPK-2 has a large value. The wear intensity in APEC compositions is also almost more than 2 times higher than the wear intensity of APPC compositions [44].

Similar results were obtained when studying the magnitude of the static electricity charge and the temperature in the friction zone, which for APEC and APPC compositions, that with an increase in the contact pressure and the coefficient of friction, respectively, an increase in the magnitude of the static electricity charge and an increase in temperature in the friction zone occur. At the same time, their lower values correspond to compositions based on polypropylene APPC [45].

When studying the tribo-thermoelectric properties of compositions based on thermoplastic polymers, during friction with raw cotton, depending on the sliding speed in the friction zone at a constant pressure value (P = 0.02 MPa), with an increase in the sliding speed, the coefficient of friction increases and, accordingly, the magnitude of the static electricity charge and an increase in temperature in the contact zone (Table 4).

Table 3. Change of tribo-thermoelectric properties of compositions based on thermoplastic polymers, during friction with raw cotton, depending on contact pressure

Composition	Coefficient of friction, f	Wear intensity, $I \cdot 10^{-10}$	The amount of static electricity charge, $Q \cdot 10^{-7}$, Kl	The temperature in the friction zone, K
P = 0,01 MPa				
APEC-1	0,28	6,62	22,3	305
APEC -2	0,28	6,41	19,4	306
APPC-1	0,27	3,19	17,6	308
APPC-2	0,26	3,08	16,8	311
P = 0,03 MPa				
APEC-1	0,29	6,7	23,7	307
APEC -2	0,29	6,6	20,3	309
APPC-1	0,28	3,23	19,1	311
APPC-2	0,27	3,12	17,3	312
P = 0,05 MPa				
APEC-1	0,32	6,94	23,9	323
APEC -2	0,31	6,73	21,4	320
APPC-1	0,29	3,21	20,1	316
APPC-2	0,28	3,16	19,7	313

Table 4. Change of tribo-thermoelectric properties of compositions based on thermoplastic polymers, in friction with raw cotton, depending on the sliding speed

Composition	Coefficient of friction, f	The amount of static electricity charge, $Q \cdot 10^{-7}$, Kl	The temperature in the friction zone, K
V = 1,0 m/s			
APEC-1	0,29	20,4	315
APEC -2	0,28	19,7	313
APPC-1	0,27	18,3	308
APPC-2	0,26	17,1	305
V = 4,0 m/s			
APEC-1	0,31	23,6	319
APEC -2	0,30	23,1	317
APPC-1	0,29	22,5	315

APPC-2	0,27	21,3	313
V = 6,0 m/s			
APEC-1	0,33	25,9	321
APEC -2	0,31	24,6	319
APPC-1	0,30	23,7	317
APPC-2	0,29	23,1	315

The data obtained on the change in the magnitude of the static electricity charge and temperature in the friction zone show that within $12\text{-}42 \cdot 10^{-7}$ Kl, the occurrence, and accumulation of electric charges, although it leads to an increase in the tension in the double electric layer in the contact zone, does not lead to a sharp increase in temperature in the friction zone, which is 305-320 K [46-50].

4. Conclusions

As a result of the conducted studies on the prevention of clogging of raw cotton with the use of compositions of thermoplastic polymers, the following has been established.

The physicomechanical and tribo-thermoelectric characteristics of the developed composite polymer materials based on thermoplastic polymers fully meet the functional requirements for materials for the working bodies of cotton machines and the mechanisms of the cotton cleaning industry.

The use of a composition of polymer materials based on polyethylene, having a relatively higher coefficient of friction than compositions based on polypropylene, provides the necessary forces for the adhesion of cotton when interacting with raw cotton in the friction nodes of cotton-transporting machines.

In a wide range of operating conditions of cotton-cleaning and cotton-processing machines and mechanisms for the manufacture of their parts from polypropylene-based compositions working in a pair of raw cotton under wear conditions provides the necessary surface characteristics of the friction pair.

In general, when using the above compositions in friction units interacting with raw cotton, it completely prevents the ignition of raw cotton, providing the necessary wear resistance, which makes it possible to recommend coatings or parts made of them for a wide industrial application.

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