Features of contact interaction of composite polymer materials with raw cotton in the process of friction

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Abstract. Based on modern concepts of the theory of wear and tear in the course of studying the process of contact interaction of composite polymer materials with raw cotton, a molecular-mechanical-electrical theory of contact interaction is put forward, which reveals the influence of the electrical components of the friction forces on the mechanism and nature of friction.

1. Introduction
As is known [1-4], the contact interaction of solids is a multifactorial process, accompanied by rather complex mecanochemical and physical phenomena caused by external and internal conditions of the material environment. It has a different nature even for one pair of solids, depending on the conditions of contact and the environment. However, the variety of conditions for the contact interaction of solids does not mean that for certain processes of contact interaction of solids, including composite polymer materials, completely satisfactory regularities cannot be obtained.

In the earliest studies of the contact interaction of solids, the study was based on the consideration of the interaction of rough surfaces of solid, absolutely rigid bodies, they were dominated by purely mechanical concepts. On the basis of this concept, a hypothesis about the mechanical nature of contact interaction of solids was first formulated, which was further developed in [2-4].

With the development of research in this area, a hypothesis was put forward that the forces of molecular attraction predominate, and that the friction force increases with a decrease in roughness due to an increase in molecular adhesion between the contacting bodies, which is a consequence of the closer approach of their contact surfaces.

In the course of studying the process of contact interaction of solids during friction, a number of theories have appeared, including the molecular-mechanical theory of friction [5-7]. According to this theory, friction is mainly caused by the deformation of the thin surface of the material layer by embedded irregularities and the resistance to fracture of the films covering the bodies. The theory is based on the assumption that in contacting there is always a relative penetration of bodies.

The increasing complexity of the conditions for mechanical loading and the physicochemical action of media, the colossal variety of materials used leads to the possibility of universally using classical concepts at the molecular level. Attempts to describe all the processes occurring during the contact interaction of bodies at the molecular level have prompted researchers to explain the activation of physicochemical processes that are inevitable during friction loading by the phenomena of chemical and physical adsorption and diffusion. Naturally, in this case, mechanical interaction began to lose its predominant importance.
2. Method

In contrast, combined theories have emerged. The combined theory, which is based on mechanical, deformation concepts and considerations of molecular-adhesive interactions, was put forward by I.V. Kragelsky [6]. Later, he proposed the molecular-mechanical theory of friction, which found the greatest acceptance. According to this theory, friction is mainly caused by the deformation of the thin surface of the material layer by embedded irregularities and the resistance to fracture of the films covering the bodies. The theory is based on the assumption that when bodies are in contact, there is always a relative penetration of bodies.

In accordance with the molecular-mechanical theory, friction forces arise not over the entire contact area, but only in separate contact zones, i.e. on the actual contact area (ACA). The resultant of these forces is the total frictional force. Moreover, friction can be carried out by mutual implantation, molecular adhesion and mutual adhesion of contacting surfaces.

The magnitude of the friction force is the sum of two components of tangential resistance - molecular and mechanical:

\[ F = F_{\text{mol.}} + F_{\text{mech.}} \]

Resistance to metal ablation, multiplied by the cross-sectional area of the track, referred to normal load, gives the mechanical component of the coefficient of friction.

The molecular component of the friction force is manifested in the form of seizure, welding, adhesion of two closely spaced solids and the destruction of the formed bonds during shear. This view is common to all bodies. Interatomic (molecular) interaction of surfaces of solids (adhesion) is manifested for any solids when they are close together and there are no protective films on them. In the presence of films, the latter interact, the nature and intensity of which is influenced by the properties of bodies, contact conditions, the possibility of the formation of an electric double layer, etc.

The friction coefficient, according to the molecular mechanical theory, is expressed by a three-term relationship:

\[ f = \frac{\tau_0}{P_r} + \beta + \kappa \alpha \sqrt{\frac{h}{R}} \]

where: \( \tau_0 \) - is the specific force of molecular interaction;
\( P_r \) - is the actual pressure;
\( \beta \) - coefficient characterizing the increase in shear strength with an increase in normal pressure;
\( K \) - is a coefficient that depends on the type of contact;
\( \alpha \) - empirical coefficient;
\( h \) - is the depth of penetration of surface irregularities;
\( R \) - is the radius of penetration of the surface roughness.

A significant contribution to the further development of the molecular-mechanical theory of friction was made by N.M. Mikhin [8], N.B. Demkin [9-11] and others. They showed that in the process of contact interaction of solids, an essential role is played not by the geometry of the surfaces of the contacting bodies and ACA, but, consequently, the deformation component of friction forces.

Thus, the analysis of the molecular and mechanical components of the friction coefficient shows that all the studies considered did not take into account the electrical phenomena arising during the contact interaction of two bodies, although they play an important role in the contact of two metals, a metal with a semiconductor, a metal with a dielectric and, especially, at contact of two dielectrics, which are polymer and raw cotton.

Raw cotton occupies an important place in the economy of the Republic of Uzbekistan. Therefore, increasing the efficiency of cotton growing through the comprehensive mechanization of all processes, from harvesting to processing cotton, increasing the efficiency and productivity of the machines and mechanisms used is the main technical and economic task facing the scientists and designers of the
republic. An analysis of the operating conditions of the main working bodies of machines and mechanisms intended for the complex mechanization of the processes of harvesting, transportation and processing of raw cotton shows that these machines and mechanisms have general and specific disadvantages, which include damage to the fiber and cotton seeds, the formation of free fiber in as a result of impact during the interaction of metal working bodies with raw cotton, the possibility of ignition of raw cotton upon impact with solid and heavy impurities present in cotton, as well as due to the occurrence of static electricity in the friction zone of a cotton-metal pair and a high coefficient of friction when interacting with raw cotton [11-12].

The working bodies of machines and mechanisms are in direct contact and are constantly in contact with raw cotton. Raw cotton has specific properties: tenacity, dependence of characteristics on its moisture content, electrification during friction with polymers, relatively easy flammability and scuffing properties. Therefore, when choosing polymeric materials for the manufacture of parts of the working bodies of these machines, it is necessary to take into account the nature and patterns of their interaction with raw cotton, the nature of wear, electrification, etc.

Proceeding from this, the task arises of studying the features of the contact interaction of composite polymer materials with pulp (raw cotton) in the process of friction, as well as the development and application of new composite polymer materials in the working bodies of cotton machines and mechanisms.

Solving the important problem of creating composite polymer materials and coatings on the basis of a comprehensive study of the nature of the contact interaction of polymer materials with raw cotton will help to increase the efficiency and efficiency of machines and mechanisms for harvesting and processing raw cotton.

In this regard, we will consider the features of raw cotton and the state of the surface of the polymer material. Raw cotton has specific properties and a complex composition. The composition of raw cotton contains 90-91% cellulose, 1.5-2.0% pentazan, 2.0% pectin substances, 1.5-2.0% proteins, 0.5-1.0% fats and wax, 2.0-3.0% of lignin, etc. It consists of fibrous (35.0% long fiber, 0.3% fiber from the beetle, 7.0% short fiber and seed padding) and non-fibrous substances (55.1 % bare seeds, 1.5% litter, 0.2% seeds from a beetle).

The quality of raw cotton is assessed in accordance with the technological instructions for the following indicators: fiber damage, seed fragmentation, number of flagella, degree of malformation, degree of formation of fumes, grade and degree of seed hairiness.

Specific features of raw cotton include: its dispersion, heterogeneity of mechanical properties due to natural (seeds) and weed impurities (solid inclusions of various origins - parts of leaves, stems, valves, etc., mineral - sand, dust and small stones). The weediness of raw cotton is characterized by two assessments: quantitative (total litter content in raw cotton) and qualitative (size characteristic of litter and its relationship with the fiber of cotton lobules). An admixture less than 8 mm in size belongs to small litter, more to large litter. Weed impurities are located both on the surface of the fibers and inside its lobules and volatiles with varying degrees of adhesion. The trash impurities on the cotton surface are actively involved in the friction process. Solid inclusions affect the process of ACA formation, since the mechanical properties of these inclusions usually differ from those of cotton fiber. In-depth and thorough studies of swollen and non-swollen fiber preparations have shown the concentric structure of cotton fiber with a known radial ordering. This structure, which is an alternation of fibrillar layers with different directions of fibrils from layer to layer, explains well the high strength of cotton fiber [13].

It is known that the presence of roughness and submicro-roughness of the contacting surfaces changes the process of ACA formation and the distribution law of the actual pressure at the points of contact. This circumstance requires the study of the geometry of the contact surfaces and the choice of a real scheme of interaction of bodies.

Polymeric and composite polymeric materials belong to the class of solids, the solidity of which is determined by two main types of bonds: homopolar (covalent) between atoms in a molecule and van
der Waals forces or hydrogen bonds between molecules [14]. Up to the glass transition temperature \( T_c \), the polymer material is a solid, in the region from the temperature \( T_c \) to the flow point \( T_f \) it softens and becomes highly elastic, above \( T_f \) it is fluid. In the process of curing, the surface of the polymer and composite polymer material acquires a kind of roughness caused by the waviness of the support or the unevenness of the coating thickness, the effect of the filler and the supramolecular structure of the binder, as a result of which waviness, microroughness and submicroroughness of the polymer coating are formed. The source of submicroscopic irregularities is the internal structure of solids. The mechanical, physical and chemical properties of thin surface layers are determined by material data, deformations arising from contact, physicochemical action of working media and temperature. The geometric parameters of the surface and the state of the material in the surface layer are interrelated. Obviously, an objective assessment of the geometric parameters of the material surface should include the characteristics of macrogeometry, microgeometry and submicrogeometry, taking into account the nature and mechanisms of the formation of geometric imperfections, i.e. with division into components associated with machining, internal structure and loading during operation.

For the first time studies of the process of contact interaction of fibrous materials with various structural materials were carried out by A.Yu. Ishlinsky [15] and I.V. Kragelsky [16]. It is shown in [15] that with an increase in the surface roughness of the material, the coefficient of friction with cotton also increases. In addition, when determining the tensile force of the free part of the fiber in contact with the spindle, as the friction coefficient increases, the tension of the free part of the fiber increases, i.e. the probability of breakage of cotton fibers increases when removing cotton wedges from bolls.

In the work [16], fundamental for the friction of fibrous substances with various materials, the influence of various factors on the coefficient of friction is investigated. Thus, it has been shown that with an increase in the sliding speed of fibrous materials over the surface of structures to a certain value, an increase in the friction coefficient is observed, and a further increase in the speed leads to its decrease. This is due to the fact that at low sliding speeds, the elastic properties of the pulp provide the time required for its penetration into the surface of the counterbody, and at sufficiently high speeds, such penetration does not occur. The noted dependence of the friction coefficient on the sliding speed is explained by the viscoelastic nature of the interaction in the metal-cotton system.

R.G. Makhkamov [17] investigated the interaction of raw cotton with the surfaces of structural materials from the point of view of optimizing the roughness of the counterbody surface, aimed at reducing the mechanical damage to the fibers. He showed that the force of interaction of raw cotton with metal surfaces increases either due to microcutting of cotton fibers on microprotrusions of the surface, or due to an increase in adhesive interactions associated with an increase in the moisture content of raw cotton. According to his data, intensive microcutting of fibers occurs when the corner radius of the vertices is less than 100 \( \mu \text{m} \). For conditions in which there will be no capture of fibers by microprotrusions of a rough surface, he recommends the following formula:

\[
\frac{2R_z}{S} \leq \frac{N\left(\mu_2 - \mu_1\right) + b_1\left[N\left(1 + \mu_1\mu_2\right) + b_2\mu_1\right] - b_1\sqrt{\left(1 + \mu_1^2\right)\left[N\mu_2 + b_2\right]^2 + N^2}}{N\left(1 + \mu_1\mu_2\right) + b_2\mu_1} - b_1^2,
\]

where \( \mu_1 \) - is the coefficient of friction of the fiber and the metal surface; 
\( \mu_2 \) - coefficient of internal friction of fibers; 
\( N \) - normal load; 
\( b_1 \) - tenacity, mainly determined by the forces of adhesion between the fiber and the metal surface; 
\( b_2 \) - fiber tenacity, determined by cohesion forces; 
\( S \) - microroughness step; 
\( R_z \) - microroughness height.

The optimal value of the radius of rounding of the tops of irregularities (100-200 microns) and the material (titanium and chromium) for the working surfaces of the main organs of cotton processing machines and mechanisms, allowing to reduce the friction forces when they interact with raw cotton, are proposed.
3. Results and Discussion
S.S. Negmatov [18, 19] for the first time carried out fundamental studies of the contact interaction of polymer and composite materials with raw cotton. Studies have shown that for most of the materials under study, with an increase in the sliding speed, the friction coefficient first increases and reaches an extremum, and then, with a further increase, it decreases. In particular, it was revealed that the dependence of the coefficient of friction of polymeric materials with raw cotton on the sliding speed at low and medium pressures has an extreme character and is described by the formula of I.V. Kragelsky [16]:

\[ f = (a + bv) e^{-cv} + d, \]

and in the zone of sufficiently large pressure values it has a complex character and is described by the formula of G.E. Svirsky [19]:

\[ f = (c_1 + c_2v^2) e^{-\lambda v} \sin v + cv, \]

where \( a, b, c, d, c_1, c_2, \lambda \) - parameters that determine friction;
\( v \) - is the sliding speed.

The influence of sliding speed and pressure in the friction zone in the polymer-cotton system on the amount of static electricity was also investigated. It was found that with an increase in speed and pressure, the amount of charge increases and is in the range of \( 12 \div 42 \cdot 10^{-7} \) Coulon.

The emergence and accumulation of electric charges leads to an increase in the tension in the electric double layer in the contact zone, which, in turn, leads to an increase in the electrical component of the friction force. The author explains this fact by the existence of energy bands of contacting materials, the orientation of the dipoles at the interface and structure, and the inhomogeneity of the contacting bodies.

During the study of the process of contact interaction of composite polymeric materials with raw cotton and in the development of the molecular-mechanical theory of friction, S.S. Negmatov put forward a molecular-mechano-electrical theory of contact interaction, in which the influence of the electrical components of friction forces on the mechanism and nature of friction was revealed [18-19].

According to this theory, the coefficient of friction consists of molecular (\( f_{mol} \)), mechanical (\( f_{mech} \)) and electrical (\( f_{elec} \)) components:

\[ f = f_{mol} + f_{mech} + f_{elec}. \]

Considering that the contact interaction in a polymer-cotton pair is carried out mainly through the fibers participating in the contact and causing an increase in the molecular component with increasing pressure, and also taking into account that molecular interaction occurs on the areas of actual contact, the formula for determining the molecular component of the coefficient friction:

\[ f_{mol} = \frac{\tau_\eta}{P_a} + \beta, \]

where \( \tau_\eta \) - shear resistance, N/m²;
\( P_a \) - nominal contact pressure, N/m²;
\( \eta_r \) - is the relative contact area of a polymer-cotton pair, which is determined by the formula:

\[ \eta_r = P_a \sqrt{\frac{8d}{\pi E' g_1 g_2}} \left[ g_2 + m A'_{nl} \left( g_1 - \sqrt{g_1 g_2} \right) \right], \]

where \( d \) - is the fiber diameter;
\( E' \) - is the reduced modulus of elasticity of the polymer-cotton system;
\( m \) - is the average number of seeds per unit area;
\( A'_{nl} \) - the area of the nominal section of the seeds;
\( g_1, g_2 \) - specific load per unit length of contact strips;
\( \beta \) - is the coefficient of strengthening of the molecular bond of the piezoelectric coefficient.
This formula establishes a direct relationship between the molecular component of the coefficient of friction and the relative ACA, which is linear. It makes it possible to analytically determine the molecular component of the coefficient of friction of a polymer-cotton pair, taking into account electrification:

\[ f_{\text{mol}} = \left( \frac{\tau_0}{G_S} \right)^* \rho^x + \beta_2 \left( 1 + \lambda \right), \]

where \( G_S \) - is a constant coefficient (N/m^2), depending on the type, physical composition and properties of raw cotton and is numerically equal to the actual pressure at the contact at a bulk density twice the initial;
\( \rho^x \) - coefficient characterizing the elastic-viscous behavior of the contact, depending on the type and physical composition of raw cotton, the type and geometry of the material surface;
\( \beta \) - piezoelectric coefficient, consists of two terms:
\( \beta = \beta_1 + \beta_2 \), \( \beta_2/\beta_1 = \chi \),

where \( \lambda \) - is thermal conductivity.

When studying the mechanical component of the friction force during the interaction of polymeric materials with raw cotton, it was found that the coefficient of friction increases with increasing irregularities. The surface condition significantly affects the friction force.

Based on the foregoing, the mechanical component of the friction coefficient for a polymer-cotton pair is determined by the formula:

\[ f_{\text{mech.}} = f_{\text{def.}} + f_{\text{eng.}}, \]

where \( f_{\text{def.}} \) - is the deformation component of the friction coefficient;
\( f_{\text{eng.}} \) - coefficient of friction, which depends on the fiber engagement with the unevenness of the pavement:

\[ f_{\text{def.}} = K \alpha K_{1} \sqrt{\frac{\Delta h}{r}}, \quad f_{\text{eng.}} = K \alpha (1 - K_{1}) \frac{h_{\text{av}}}{d}, \]

where \( h_{\text{av.}} \) - is the average depth of fiber penetration into microroughnesses of coatings;
\( K_{1} \) - the proportion of solids in raw cotton involved in interaction with the surface of the polymer material;
\( K \) - is a coefficient that depends on the type of contact;
\( \Delta h \) - the depth of penetration of solid irregularities of raw cotton substances into the surface of the polymer coating;
\( r \) - radius of curvature of the tops formed as a result of the interaction of raw cotton and polymer coating;
\( d \) - cotton fiber diameter;
\( \alpha \) - empirical coefficient.

Then the mechanical component of the friction coefficient will have the form:

\[ f_{\text{mech.}} = K \alpha K_{1} \sqrt{\frac{\Delta h}{r}} + K \alpha (1 - K_{1}) \frac{h_{\text{av}}}{d}. \]

Thus, the mechanical component of the friction coefficient mainly depends on the value of the relative penetration \( (h_{\text{av.}}/r) \) and the conditions of fiber engagement \( (h_{\text{av.}}/d) \), as well as on the proportion of solids \( K_{1} \) in the interaction zone. From this it follows that when fibrous materials friction with a polymer material, in contrast to the friction of solids, an engagement process occurs, the value of which is determined by the engagement condition \( (h_{\text{av.}}/d) \) and their proportions \( (1-K_{1}) \).

4. Conclusions

According to the molecular-mechano-electric theory of friction, the formula for the coefficient of friction will have the form:

\[ f = \left( \frac{\tau_0}{G_S} \right)^* \rho^x + \beta(1+\lambda) + \frac{K \alpha K_{1}}{2} \left[ \sqrt{\Delta h} + \left( \frac{1}{K_{1}} - 1 \right) \frac{h}{d} \right]. \]

Thus, using the features of the contact interaction of polymeric materials with raw cotton and in
accordance with the molecular-mechano-electrical theory of friction, it is possible to select materials and fillers for the development of new composite polymer materials [20, 22], to purposefully change and regulate the properties of materials, providing their compliance with the requirements for composite polymeric materials working in interaction with raw cotton. However, the possibilities of increasing the durability, performance and efficiency of composite polymer materials have not yet been fully exhausted. In this regard, further research in this area should be focused on a deeper disclosure of the mechanism of contact interaction in the polymer-cotton system and the process of friction of composite polymer materials with a fibrous mass.

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