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Tribotechnical processes of the soil environment interaction with the working bodies of soil tillage and earthmoving machines reinforced with composite materials

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Abstract

The work presents the study results of the stress-strain state of the soil, as a continuous medium filled with abrasive particles under the action of the working bodies of soil tillage and earthmoving machines. One of the main properties of the soil, which determines the specifics of the force interaction of the working surfaces of the working bodies of soil tillage and earthmoving machines with the technological environment, is taken into account, namely the tendency of the contact layer of the treated layer to compaction.

The relationship between stress in the soil and the wear of the working bodies of soil tillage and earthmoving machines has been established experimentally. A theoretical analysis is presented for the stress-strain state of the local region of the strengthened surface layer that is used in the working bodies of soil tillage and earthmoving machines, in which the filler, inclusion or strengthening phase is placed.

An analysis of the contact characteristics of the stress-strain state and their changes during friction and wear was carried out based on the formulation and solution of the contact interaction problems of abrasive soil particles with the inhomogeneities of the composite coatings components based on ultra-high molecular weight polyethylene with fillers during strengthening of the working bodies of soil tillage and earthmoving machines.

Computer modeling was performed to study the nature of stress distribution in the reinforced surface layer of the working bodies of soil tillage and earthmoving machines in the area of the contact zone in stationary and dynamic conditions. The contact problem is formulated, the boundary conditions and the solution in the form of components of the stress field are given. The characteristics of the filler, their content in the composite material and coating are taken into account, the relationship between the stress-strain state and wear is established.

Key words: stress, contact, wear-resistant coatings, filler, composite material, ultra-high molecular weight polyethylene, working body of soil tillage and earthmoving machine

Introduction

Modern agrotechnological trends in soil cultivation by the working bodies of soil tillage and earthmoving machines (WBSTEM) set requirements for the producers of the agro-industrial sector to increase reliability and reduce energy and material costs of such machines for their cultivation.

One of the main properties of the soil, which determines the characteristic of the force interaction of the working surfaces of the WBSTEM with the technological environment, is the propensity of the contact area of the tillage layer to compaction [1]. In the process of tillage, the movement of cutting element (CE) of WBSTEM leads to partial compaction of soil particles in its layer, which are in contact with the working surface, as well as in the contact layer. The fractional redistribution of soil abrasive particles (AP) is accompanied by a decrease in the distance between them, pressing into the part of the layer above the cutting element and the formation of a reaction force.

Mechanics of contact interaction is one of the leading directions in agricultural mechanics. Despite the fact that solutions to a large number of contact problems have been obtained by both analytical and numerical methods, the creation and study of contact interaction models remains relevant even today in connection with the development of new composite materials and technologies, such as strengthening, due to the variety of processes and phenomena occurring in the contact zone during friction and wear of the surfaces of the working bodies of WBSTEM, introducing new requirements for their operating conditions.

When setting classical contact problems, the model of a homogeneous isotropic body is mainly used and the interaction of smooth surfaces is considered [1, 2]. With the development of mathematical apparatus and rapid growth in computational power it became possible to take into account surface roughness and the viscoelastic properties of contacting bodies, the presence of films and coatings on the contact surface, the occurrence of adhesion, friction and wear phenomena when solving contact problems.

Research of contact interaction with bodies that have inhomogeneities of a mechanical, geometric and tribotechnical nature, creation of material models of triboelements (TE), working (technological) environments, formation of secondary structures (SS), movement of the boundary between phases under thermomechanical influences [3] is of increased interest both from the point of view of fundamental and applied science. Attention should be paid to research in the following directions: the introduction of additional parameters of the surface layers state of the WBSTEM and the contact zones with the particles of the soil environment, the determination of the ratios for these parameters, the experimental verification of the created physical and mathematical models, as well as the consideration of interphase boundaries during the strengthening of the surface layer of the WBSTEM and the kinetics of the new phase [4].

The improvement of any technological process of soil cultivation implies a decrease in its energy intensity.

The development of modern areas of materials science is associated with the development and application of promising materials based on various initial components, with the involvement of a wide range of resources and technologies, using different research methods, with the modification of components in order to obtain materials with improved properties or acquiring new functional properties that allow expand the scope of their application [1–8].

A promising material with a wide range of functional properties, which is used today in the field of production of WBSTEM to solve various tasks of increasing wear resistance and energy efficiency, is ultra-high molecular weight polyethylene (UHMWP). The advantages of UHMWP are a combination of high wear resistance, resistance to aggressive environments, low coefficient of friction, high impact strength, low brittleness temperature, which allows the use of products based on UHMWP, including extreme operating conditions (the brittleness temperature of the material is up to -200 °C) [2]. The limiting factors for the use of UHMWP are the low melting point (135–190 °C), due to which the upper limit of the material's operating temperature is 90 °C, as well as the high viscosity of the polymer melt, which complicates the process of its processing [3].

Inclusions, fillers, new phases are not only stress concentrators, but also their source, the local density changes, residual stresses arise. Technological residual stresses during the strengthening of WBSTEM can play both a positive and a negative role in the process of operation.

Literature review

A classic work, which presents a model for determining residual stresses caused by phase transformations in an unbounded body, is work [5]. This model, based on the solution of the planar problem of the theory of elasticity, determines the residual stresses inside local areas, inclusions, fillers, and phases and are resolved by means of a boundary transition. At the same time, it is assumed that the elastic characteristics do not change during the transformation process.

The solution of the planar periodic contact problem for the stamp system, taking into account the frictional forces, is given in works [1,4], where there is also an analysis of the stress-strain state of the surface layers. In [7], a periodic contact problem for a surface with sinusoidal undulations in two mutually perpendicular directions is considered. The general method of solving spatial and flat contact problems with wear at a constant contact area is described in [8]. The contact condition using the linear law of wear and integral representation of elastic movements due to contact pressure allows reducing the problem to the determination of eigenvalues and eigenfunctions of some integral operators. It has been proven that the pressure distribution at the point of contact assumes a stationary value during a steady mode of wear.

In works [9, 10], as well as in monographs [11, 13], mathematical formulations of a number of wear-contact problems for heterogeneous elastic bodies with variable surface wear resistance are considered. Such tasks arose in connection with the strengthening of WBSTEM with composite materials (CM) and composite coating (CC), local strengthening of their working surfaces. Some types of continuous surface strengthening are also taken into account, in particular with laser technologies, when it is impossible to achieve a uniform change in the surface structure of the WBSTEM. The latter issues play a decisive role in the problem of increasing the reliability and wear resistance of WBSTEM, and therefore require a solution.

Purpose

An analysis of the contact characteristics of the stress-strain state and their changes during friction and wear was carried out based on the formulation and solution of the problems of contact interaction of soil particles with inhomogeneities of CM (CC) components based on ultra-high molecular weight polyethylene with fillers during strengthening of WBSTEM.

Methods

In the interaction process of WBSTEM with the soil, the latter undergoes a certain deformation, the load amount and bulk mass are constantly changing [4]. The movement of the working body causes compression deformations of the internal stress of the soil environment, the direction of action of which coincides with the direction of the absolute movement of soil particles of the compressed volume (contact layer), and the intensity decreases as it moves away from the executive surface into the depth of the interacting part of the formation.

Deformation of dense soil at a low stress level leads to an increase in volume, that is, its dilatation (volumetric expansion). Since the soil becomes less dense in places where the volume increases, which contributes to further deformation and increase in volume, the process is unstable. This indicates that deformations in the soil can concentrate, which leads to the appearance of fracture surfaces. Along the surfaces of the fracture, there are very thin expansion bands that differ in properties from the main mass of the soil. Deformation in dilation bands is greater in cases of shear failure than tensile failure, since friction processes are taken into account.

For a theoretical analysis of this influence, we will use the equation of mechanics of mixtures [13]. The condition of quasi-static deformation of heterogeneous materials can be presented in the form of an equilibrium equation:

$$\partial\overline{\sigma_{ij}^{(k)}} \cdot c_k/\partial x_i = 0, \tag{1}$$

where $\overline{\sigma_{ij}^{(k)}}$, c_k are the averaged component of the stress tensor and the content for the *k*-th component (phase) of the CM (CC). At the same time, the stress state in local areas has two components:

$$\sigma_{ij}^{(R)} = \sigma_{ij}^{(1)} + \sigma_{ij}^{(2)}. \tag{2}$$

where $\sigma_{ij}^{(1)}$ - stressed state of an infinite elastic plane with a filler (inclusion) of spherical shape;

$\sigma_{ij}^{(2)}$ - stressed state of the half-plane resulting from the action of a distributed load on its boundary (z = 0):

$p_f(x) = -\sigma_z^{(2)}|z = 0,\ q_f(x) = -\tau_{xz}^{(1)}|z = 0,$

which is introduced to implement boundary conditions. For this, it is necessary to fulfill the equality:

$$p_f(x) = \sigma_z^{(1)}|z = 0,\ \ q_f(x) = -\tau_{xz}^{(1)}|z = 0 \tag{3}$$

Solving the contact problem for a filler of size *r* makes it possible to estimate the stress $\sigma_{ij}^{(1)}$ in the cylindrical coordinate system:

$$\sigma_x^{(1)} = \begin{cases} -A, & x^2 + z^2 < r^2; \\ -Ar^2\frac{x^2-z^2}{(x^2+z^2)^2}, & x^2 + z^2 > r^2, \end{cases} \tag{4}$$

$$\sigma_z^{(1)} = \begin{cases} -A, & x^2 + z^2 < r^2; \\ -Ar^2\frac{x^2-z^2}{(x^2+z^2)^2}, & x^2 + z^2 > r^2, \end{cases} \tag{5}$$

$$\tau_{xz}^{(1)} = \begin{cases} 0, & x^2 + z^2 < r^2; \\ -2Ar^2\frac{xz}{(x^2+z^2)^2}, & x^2 + z^2 > r^2, \end{cases} \tag{6}$$

Solving the contact problem to find the stress $\sigma_{ij}^{(2)}$ requires following boundary conditions:

$$p_f(x) = \begin{cases} -A, & |x| < r; \\ Ar^2\frac{1}{x^2}, & |x| > r, \end{cases} \qquad q_f(x) = 0\ , z = 0. \tag{7}$$

If a normal load is applied to the boundary of the half-plane, then the stress components $\sigma_x^{(2)}$, $\sigma_z^{(2)}$ $\sigma_{ij}^{(2)}$ and $\tau_{xz}^{(2)}$ that are acting in the half-plane are as following:

$$\sigma_x^{(2)} = -\frac{2z}{\pi}\int_{-\infty}^{\infty}\frac{p_f(s)(x-s)^2ds}{((x-s)^2+z^2)^2}, \sigma_z^{(2)} = -\frac{2z^3}{\pi}\int_{-\infty}^{\infty}\frac{p_f(s)ds}{((x-s)^2+z^2)^2}, \tau_{xz}^{(2)} = -\frac{2z^2}{\pi}\int_{-\infty}^{\infty}\frac{p_f(s)(x-s)ds}{((x-s)^2+z^2)^2}. \tag{8}$$

The study of the distribution of stresses in the area of local contacts of the surface reinforced layer of WBSTEM CM (CC) shows that the stress-strain state in these areas is a concentrator of residual stresses, and the most dangerous place, from the destruction point of view, is the area of the main material near the surface of the half-space. This result is in good agreement with experimental research and simulation data. A local maximum τ_{max} occurs on the axis of symmetry of the filler in the main material.

When studying the contact interaction of soil particles and an elastic half-space with fillers (inclusions) coming to the surface, it was assumed that the main material and the filler material (inclusions) are elastic and have the same Young's moduli E and Poisson's ratios μ. At the same time, the boundary conditions on the surface of the half-space at z = 0 are as follows:

$$\sigma_z|z=0=\begin{cases}p(x,y) & (x,y)\in\Omega\\ 0 & (x,y)\notin\Omega\end{cases},\quad \tau_{xz}|z=0=\tau_{yz}|z=0=0, \tag{9}$$

where $p\ (x, y)$ is a pressure inside the contact area.

It is assumed that the stress state that occurs during contact interaction does not lead to a change in the shape and size of the filler (inclusion) and the problem of determining the internal contact and residual stresses can be solved separately.

The stressed state of the half-space with a filler (inclusion) during contact interaction is determined by the superposition method:

$$\sigma_{ij}=\sigma_{ij}^{(C)}+\sigma_{ij}^{(R)}, \tag{10}$$

where $\sigma_{ij}^{(c)}$ - internal stresses arising as a result of contact interaction,

$\sigma_{ij}^{(R)}$ - residual stresses.

When solving the specified contact problem, the stress components are determined by ratios:

$$\sigma_x^C=-\frac{1}{2\pi}\iint_\Omega p\,(\xi,\eta)\left(\frac{z}{r^3}\left(\frac{3(x-\xi)^2}{r^2}-(1-2\mu)\right)+(1-2v)\left(\frac{(y-\eta)^2+z^2}{r^3(z+r)}-\frac{(x-\xi)^2}{r^2(z+r)^2}\right)\right)d\xi d\eta; (11)$$

$$\sigma_y^{(C)}=-\frac{1}{2\pi}\iint_\Omega p\,(\xi,\eta)\left(\frac{z}{r^3}\left(\frac{3(y-\eta)^2}{r^2}-(1-2\mu)\right)+(1-2v)\left(\frac{(x-\xi)^2+z^2}{r^3(z+r)}-\frac{(y-\eta)^2}{r^2(z+r)^2}\right)\right)d\xi d\eta; (12)$$

$$\sigma_z^{(C)}=-\frac{1}{2\pi}\iint_\Omega 3p\,(\xi,\eta)\frac{z^3}{r^5}d\xi d\eta; \tag{13}$$

$$\tau_{xy}^{(C)}=-\frac{1}{2\pi}\iint_\Omega p\,(\xi,\eta)\left(\frac{z}{r^3}\left(\frac{3(x-\xi)(y-\eta)z}{r^2}-(1-2\mu)\right)+(1-2v)\frac{(x-\xi)(y-n)(z-2r)}{r^3(r+z)^3}\right)d\xi d\eta; (14)$$

$$\tau_{yz}^{(C)}=-\frac{1}{2\pi}\iint_\Omega 3p\,(\xi,\eta)\frac{(y-\eta)z^2}{r^5}d\xi d\eta,\ \tau_{xz}^{(C)}=-\frac{1}{2\pi}\iint_\Omega 3p\,(\xi,\eta)\frac{(x-\xi)z^2}{r^5}d\xi d\eta, (15)$$

where $r^2=(x-\xi)^2+(y-\eta)^2+z^2$, and the distribution of residual stresses $\sigma_{ij}^{(R)}$ is calculated by the formula:

$$\sigma_{ij}^{(R)}=v\left(\sigma_x^{(R)}+\sigma_z^{(R)}\right) \tag{16}$$

At the same time, it is assumed that the indenter or a soil particle is spherical. Then the distribution of contact pressures is determined by the theory in works [1, 13], and the contact plane is a circle of radius *a*.

Let's consider the stress-strain state of the surface layer of the WBSTEM upon contact with the AP of the soil from an analytical point of view. The rate of change of the energy of the CM (CC) in the volume V_{sl} bounded by the surface of S_{fr} is equal to:

$$\int_V\frac{dU}{dt}dV_{sl}=\int_V\left(\frac{\partial\overline{v_i^{(k)}\sigma_{ij}^{(k)}}}{\partial x_i}\cdot c_k-\Delta U_{ic}\right)dV_{sl}, \tag{17}$$

where dU/dt, ΔU_{ic} – rate of change of internal energy and change of energy of interaction between AP and components (phases) of CM (CC);

$v_i^{(k)}$ – speed of the *i*-th AP interacting with the *k*-th component (phase).

On the other hand, there is a following equation for the plane of contact interaction:

$$\int_V dU/dt\,dV_{sl}=V\int_V\overline{v_i^{(k)}\sigma_{ij}^{(k)}}\cdot c_k\cdot n_j\,dV_{sl}, \tag{18}$$

where n_j – projection of the normal on the x-axis to the plane of contact interaction of the AP with the region of the *k*-th component (phase) of the CM (CC).

Taking into account the stress-deformed state of the surface layer of CM (CC) during friction and wear, the right-hand side of expression (17) takes the following form:

$$\int_V\overline{v_i^{(k)}\partial\sigma_{ij}^{(k)}}\cdot c_k dV_{sl}/\partial x_i+\int_V c_k\overline{\sigma_{ij}^{(k)}\varepsilon_{ij}^{(k)}}\,dV_{sl}=0{,}5\int_V c_k\overline{\sigma_{ij}^{(k)}\left(\partial v_i^{(k)}/\partial x_i+\partial v_j^{(k)}/\partial x_j\right)}\,dV_{sl}, \tag{19}$$

where $\varepsilon_{ij}^{(k)}$ – components of the strain tensor of *k*-th component;

v_i, v_j – velocity components on the corresponding axis x_i, x_j of the contact plane of the *i*-th AP with the *k*-th component (phase). The specific potential energy of deformation of CM (CC) is equal to:

$$U_{sen}=0{,}5\cdot c_k\overline{\sigma_{ij}^{(k)}}\cdot\overline{\varepsilon_{ij}^{(k)}}. \tag{20}$$

In the case of two-component CM (CP), we have the following equation:

$$U_{sen} = 0{,}5 \cdot \left(c_{v1} \left(\overline{\sigma_{ij}^{(1)}} \cdot \overline{\varepsilon_{ij}^{(1)}} + \Delta \left(\overline{\sigma_{ij}^{(1)}} \cdot \overline{\varepsilon_{ij}^{(1)}} \right) \right) + c_{v2} \overline{\sigma_{ij}^{(2)}} \cdot \overline{\varepsilon_{ij}^{(2)}} \right), \quad (21)$$

where c_{v1}, c_{v2} – corresponding matrix and filler content in CM (CC): $c_{v1} + c_{v2} = 1$.

The change in the specific potential energy of deformation at the "filler-matrix" interface is equal to:

$$\Delta U_{sen} = 0{,}5 \cdot c_{v1} \cdot \Delta \left(\overline{\sigma_{ij}^{(1)}} \cdot \overline{\varepsilon_{ij}^{(1)}} \right). \quad (22)$$

Deformation hardening of CM (CC) is determined by the expression:

$$\Delta\sigma_{c_2} = k_{зм} \bar{\lambda}^{-0,5} = K_{kr} \cdot \left(\varepsilon / \bar{\lambda} \right)^{0,5}, \quad (23)$$

where k_{str}, K_{rb} – respectively, parameters characterizing the physical essence of strengthening and robustness and structural factors of CM (CC) [14]; $\overline{\lambda}$ – the average distance between filler particles. Constant k_{str} is estimated by the formula:

$$k_{str} = C_f C_{op} E_{cm(cc)} \cdot b_B \left[\rho + \left(C_f C_{op} \rho_d + 1/b_B \right) \varepsilon \right]^{0,5}, \quad (24)$$

where C_f, C_{op} – respectively steel, characterizing the conditions of formation and operation of CM (CC); $E_{cm(cc)}$ – elastic modulus of CM (CC); b_B – Burgers vector; ρ_d – density of dislocations generated on the surface of separation of components (phases). According to Orovan's theory, supplemented [4], the k_{str} K_{rb} constant is equal to:

$$K_{kr} = \alpha_d E_{cm} {b_B}^{0,5} c_2^{0,25} \cdot K_f, \quad (25)$$

where α_d – constant value characterizing the deformation conditions; K_f – filler shape parameter:

$$K_f = \overline{\lambda} / \left(\left(\overline{\lambda} - \overline{d_c} \right)^2 + \overline{S}_{ac}^2 \right)^{0,5}, \quad (26)$$

where $\overline{d_c}$ – average size of components (phases); $\overline{S}_{ac}^2$ – the average distance between the axes of components (phases) of CM (CC). If correlation $\bar{d}_c / \overline{\lambda} \in [0;1]$, then $K_f \in [2; 5]$.

To evaluate the influence of the phase transition (PT) during the formation of CM (CC) and deformation due to friction and wear, consider the strengthening of the matrix during the formation of the martensitic phase [12]. At the same time, according to [11], the stresses in the matrix are equal to:

$$\sigma_m = c_{0m} n_m (c_m)^{n_m}, \quad (27)$$

where c_{0m}, n_m – constant coefficients characterizing the flow of PT in the CM (CC) matrix; c_m – martensite content. Taking into account the autocatalytic nature of the martensitic transformation when coherent deformations occur in retained austenite, we have:

$$c_m = k_{1m} \varepsilon^{n_c} c_A. \quad (28)$$

where $k_{1м}$ – the proportionality coefficient characterizing the intensity of the flow of martensitic PT; n_c – exponent that takes into account the catalytic effect; c_A – the content of austenite in the CM (CC) matrix. Because $c_m + c_A = 1$, then from (28) we have the following equation:

$$c_m / (1 - c_m) = k_{1m} \varepsilon^{n_k}. \quad (29)$$

This dependence is confirmed by experimental data and is consistent with the data of the work [14]. According to the autocatalytic nature of the martensitic transformation, n_c=3. Considering formula (29), we have:

$$c_m = k_{1m} \varepsilon^3 / (1 + k_{1m} \varepsilon^3); \qquad c_A = (1 + k_{1m} \varepsilon^3)^{-1}. \quad (30)$$

In the process of friction and wear, the deformation strengthening of the surface layer of CM (CC) can be characterized by the ratio [13]:

$$\sigma = k_{str} [ln(1 + \varepsilon)]^{p_s}; \qquad \Delta\sigma = \sigma - \sigma_s = h_s \Delta\varepsilon^{a_s}, \quad (31)$$

where k_{str}, p_s, h_s, a_s – parameters of strain strengthening; $\Delta\varepsilon$ – the amount of deformation without an elastic component corresponding to the yield strength σ_y.

Based on relations (30) and (31), we have the following equation:

$$\sigma = k_{str} [ln(1 + \varepsilon)]^p [1 - (1 + 1/k_{1m} \varepsilon^3)^{-1}] + \sigma_m (1 + 1/k_{1m} \varepsilon^3)^{-n_{str}}, \quad (32)$$

where n_{str} – indicator of matrix strengthening by the formation of martensite.

According to the work [14], the parameter p_s=0,18, and σ_m is the stress of the matrix material, which consists entirely of martensite and depends on the strength of the martensite and the carbon content of the steel. This is explained by the proportionality of the formation rate of martensite nuclei to its volume fraction [5].

The change in stress at the PT during friction and wear of the CM (CC) is equal to:

$$\Delta\sigma_p = \frac{k_{str}^{cs}\Delta\varepsilon^a}{\sqrt{d}}\left(1-\left(1+\frac{1}{c_1\varepsilon^3}\right)^{-1}\right)+\sigma_m\left(1+\frac{1}{c_1\varepsilon^3}\right)^{-str}, \quad (33)$$

where $k_{str}^{cs} = C_f C_{op} r^{cs} \cdot E_m b^2$; r^{cs} – parameter of the cellular dislocation structure. With a uniform distribution of dislocations $r^{cs} = 1$.

Since friction and wear is a non-stationary process, the accumulated energy of elastic-plastic deformation is equal to:

$$U_{el}(t) = \int_0^{\varepsilon} \sigma(\varepsilon)d\varepsilon, \quad (34)$$

where $\sigma(\varepsilon)$ is determined by equation (33). Knowing the values U_{spec}, or U_{el}, q_{cr} – critical power of flow density, the amount of wear can be estimated:

$$u = C_f C_{op}/q_{kr} = C_f C_{op}/U_{spec}^{3/2}. \quad (35)$$

In the case of a two-phase CM (CC), we have:

$$U_{el} = \int_0^{\varepsilon_l} \Delta\sigma_{c_2} d\varepsilon = C_f C_{op} \cdot \varepsilon_{ml}{}^{3/2}/\sqrt{\bar{\lambda}^n}; \qquad u = C_f C_{op}\bar{\lambda}^{3/4} c_m^{-3/8}\varepsilon_{ml}^{-9/4}, \quad (36)$$

where ε_{ml} – the limit value of deformation of the matrix material.

The deformation of two-phase CM (CC) can be estimated using the formula:

$$\varepsilon_{cm(cc)} = \varepsilon_{dm} - \Delta\varepsilon = \varepsilon_{dm} - C_f C_{op} \cdot \varepsilon_m c_2 = \varepsilon_{dm} - a \cdot c_n/\bar{\lambda}^n, \quad (37)$$

where ε_{dm} – matrix deformation at c_n=0; $\Delta\varepsilon = f(c_n, \lambda)$ – reduction of plasticity due to the presence of a brittle phase (filler); ε_m – matrix deformation: $\varepsilon_m = C_f C_{op}/\bar{\lambda}^n$; a, n – steels determined experimentally. If expression (37) is substituted into (36), we get the following:

$$u = C_f C_{op}\lambda^{3/4} c_n{}^{-3/8}\left(\varepsilon_{dm} - a \cdot c_n/\bar{\lambda}^n\right)^{-9/4}. \quad (38)$$

Results

During the interaction of WBSTEM with the soil, three types of soil deformations can be identified:
- microscale deformation within dilatation bands along the fracture surface;
- mutual rolling and sliding of the formed soil particles;
- deformation within soil particles, which is possible due to high soil moisture.

In the first two cases, the deformation is accompanied by an increase in volume, in the latter, compaction of soil particles may occur. Therefore, in the process of interaction of WBSTEM with the soil, the following deformations can also be distinguished: at a constant volume; during compaction; during expansion in the process of destruction. In field conditions, the general deformation of the soil consists of a collection of its various types, but one of them is the leading one.

When describing the interaction of WBSTEM with the soil layer, the theories of continuous deformable environments are quite acceptable. This approach allows to describe the process of deformation, movement and mixing of soil particles on the working surface of the WBSTEM. Without researching these processes, it is impossible to establish the regularities of the interaction of WBSTEM with the soil and to describe the stress-strain state of the soil.

Research shows that by comparing the natural volumetric mass of the soil with the optimal one, it is possible to determine the rational method of cultivation and the degree of action on the soil. The results of the study of the amount and nature of the wear of standard WBSTEM during operation indicate their dependence on the type of soil, the ratio of phase components and the stress-strain state. The dependence of the wear of cutting elements (CE) on the amount of stress in the soil layer adjacent to the WBSTEM is shown in Fig. 1.

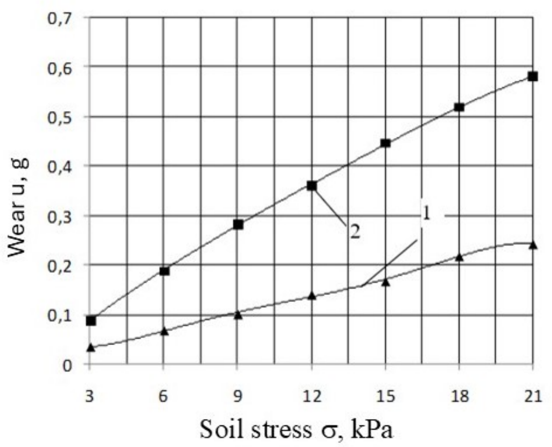


Fig. 1. Dependence of the wear of the toe of the one-sided paw (1) and the horizontal CE slot cutter (2) on the amount of soil stress in ordinary black soil (L=8,52 km, v= 1,4 m/s, W=10%)

It is shown that the wear of CE of WBSTEM increases with an increase in soil stress.

At that time, during the interaction of abrasive particles (AP) of the soil with the surface of WBSTEM, strengthened by CM (CC), the values of the components of the stress tensor σ_{ij} change in the local areas of the surfaces. The results of computer modeling of the stress fields during the action of high frequency on the working surface of the WBSTEM, carried out according to the developed methodology [14], in cases with unreinforced and strengthened CM (CC) TE in the mode of static and dynamic loading are shown in Fig. 2.

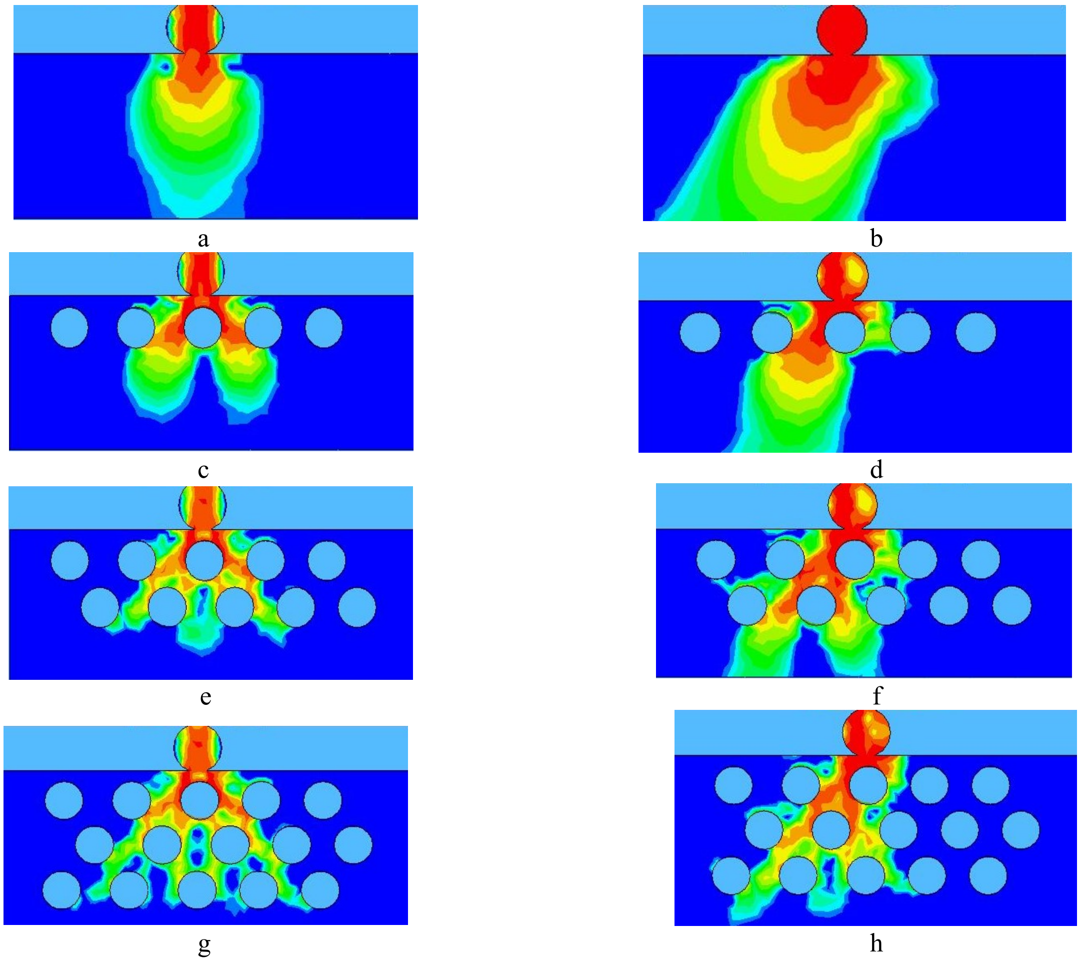


Fig. 2. Characteristic graphs of stresses in the contact areas of WBSTEM when acting on the surface of the WBSTEM: a – without coating $\overline{v} = 0$; b – without coating $\overline{v} \neq 0$; c – with a single-layer CC on TE-2, $\overline{v} = 0$; d – with a single-layer CC, $\overline{v} \neq 0$; e – with two-layer CC on TE-2, $\overline{v} = 0$; f – with two-layer CC, $\overline{v} \neq 0$; g – with a three-layer CC, $\overline{v} = 0$; h – with a three-layer CC, $\overline{v} \neq 0$

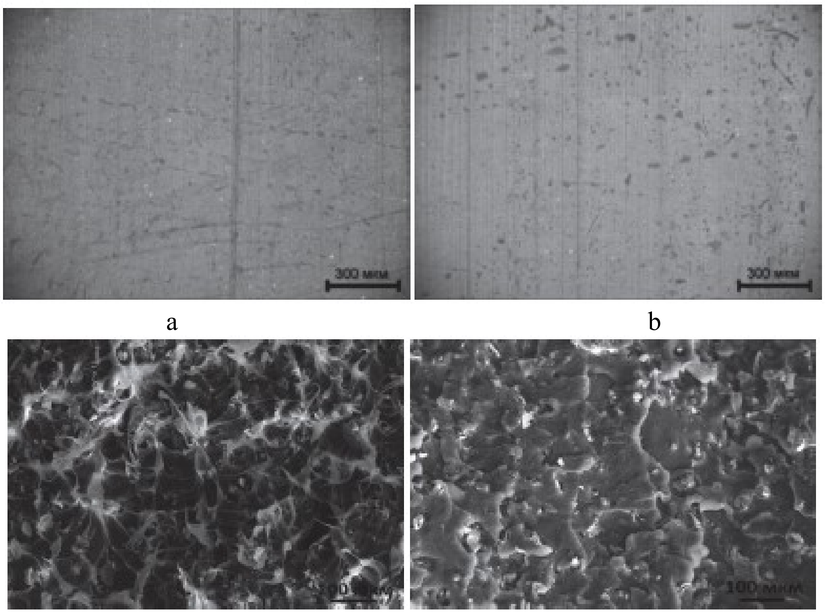
It can be seen that the region of the stress-strain state of the zone of contact with the AP is concentrated in the reinforced layer of the CM (CC), and in the dynamic load mode, the stress profile is transformed in the direction of the relative movement of the TE (Fig. 2, b, d, e, h).

Experimental studies have determined that the wear resistance of CM (CC) is primarily due to the presence of the strengthening component molybdenum disulfide MoS_2 in 5 and 10 wt.% with preliminary dispersion (filler, inclusion, phase) and phase transformation in the matrix.

The development of a mechanism for increasing the wear resistance of composites based on UHMWP during the interaction in the WBSTEM-soil tribosystem involves taking into account a number of factors:

- lack of interphase interaction between the polymer matrix and filler particles pressed deep, which determines effective absorption of energy without destruction of the composite during triboloading;
- the effect of filler particles on a change in size and shape, which in the vast majority of cases is accompanied by a noticeable decrease in mechanical properties, but may not lead to a decrease in wear resistance;
- interaction of the surface of the steel counterbody with the polymer matrix and filler particles protruding above its surface.

The microstructure of the surface reinforced layers of CE of WBSTEM was studied using a PEM 106 microscope. The PEM method allows studying the topography and chemical composition of the surface without prior mechanical processing or etching.



c d

Fig. 3. The microstructure of the friction zones of the surface strengthened layers of CE of WBSTEM UHMWP: a, c - MoS_2 5 wt.%, b, d - MoS_2 5 wt.%,

In the compositions of UHMWP MoS_2 *n* wt.% the smoothest wear surface is observed in the composition at the content of MoS_2 10 wt.%. A different pattern of changes in the supramolecular structure is observed with increasing filler content MoS_2, which determines the nature of samples destruction of experimental compositions.

Conclusions

1. The stress-strain state of the soil as a continuous solid medium under the action of the WBSTEM was considered, and the dependence of wear on the stress in the soil for different types of WBSTEM was experimentally revealed.

2. The solution of the contact problem of an abrasive soil particle action on the strengthened CM (CC) and the unreinforced surface layers of WBSTEM was considered using the method of computer modeling of stress fields. It was found that particles of fillers (inclusions) redistribute stress fields in both static and dynamic cases, and for a given CM (CC) there is a certain thickness of the strengthened layer when the stress field is completely concentrated in it.

3. From a theoretical point of view, based on the boundary conditions, the field of residual and contact stresses of the surface layers strengthened by CM (CC) under loading by the action of an abrasive particle as an indenter is considered.

4. Taking into account the stress-strain state, strain hardening and evaluation of the effect of phase transformation during the formation and deformation of CM (CC) during friction and wear are considered. These are primarily martensitic-austenitic transformations. The relationship between stress in the surface layer of CM (CC) and wear characteristics was established, which makes it possible to design an effective reinforced layer on WBSTEM.

5. Experimental studies have shown that the wear resistance of CM (CC) is primarily due to the presence of the strengthening component molybdenum disulfide MoS2 in 5 wt.% and 10 wt.% with preliminary dispersion (filler, inclusions, phases) and phase transformation in the matrix.

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Тихий А.А., Аулін В.В., Пашинський М.В., Боровік А.Є. Триботехнічні процеси взаємодії середовища ґрунту з робочими органами ґрунтообробних та землерийних машин, зміцненими композиційними матеріалами

В роботі наведено результати дослідження напружено-деформованого стану середовища ґрунту, як безперервної моделі наповненої абразивними частинками, під дією робочих органів ґрунтообробних і землерийних машин. Враховано одну з основних властивостей ґрунту, що визначає характеристику силової взаємодії робочих поверхонь робочих органів ґрунтообробних і землерийних машин з технологічним середовищем, а саме схильність контактного шару оброблюваного пласту до ущільнення.

Експериментальним шляхом встановлено зв'язок напруження в середовищі ґрунту з величиною зносу робочих органів ґрунтообробних і землерийних машин. Представлено теоретичний аналіз напружено-деформованого стану контактуючої області зміцненого поверхневого шару робочих органів ґрунтообробних і землерийних машин, з наповнювачем, включеннями або зміцнювальною фазою.

Проведено аналіз контактних характеристик напружено-деформованого стану та їх зміни при терті та зношуванні на основі постановки і розв'язання задач контактної взаємодії абразивних частинок ґрунту з неоднорідностями компонентів композиційних покриттів на основі надвисокомолекулярного поліетилену з наповнювачами при зміцненні робочих органів ґрунтообробних і землерийних машин.

Виконано комп'ютерне моделювання для дослідження характеру розподілу напружень в зміцненому поверхневому шарі різальних елементів робочих органів ґрунтообробних і землерийних машин в області контактної зони в стаціонарних та динамічних умовах. Сформульована контактна задача, наведено граничні умови та розв'язок у вигляді складових поля напруження.

Враховано характеристики наповнювача, їх вміст в композиційному матеріалі і покритті, встановлено зв'язок між напружено-деформованим станом і величиною зносу.

Keywords: напруження, контакт, зносостійкі покриття, композиційний матеріал, наповнювач, надвисокомолекулярний поліетилен, покриття, знос, робочий орган ґрунтообробної та землерийної машини.