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Research article

Influence of Soil Humidity on the Regularities of Destruction of Low-Alloy Steel During Wear

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Abrasive wear
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A B S T R A C T

When moving in soils of different humidity, a mechanochemical form of abrasive wear occurs on the working surface of low-alloy steel. The role of water in the formation of wear resistance is to regulate active deformation and fatigue phenomena on the friction surface through its simultaneous cooling, adsorption and physical-mechanical effects on the properties of metal, soil and abrasive particles. The nature of the dependence of wear resistance on moisture with changes in the mechanical composition of the soil is determined by the relationships between the rates and intensities of the indicated effects of water. The influence of humidity on wear resistance in soils of different mechanical composition is carried out through the rheological-fatigue parameter in the following dependence: the greater the rheological-fatigue parameter, the higher the wear resistance of the steel. Based on this, the mechanical component of contact interaction should be recognized as determining the strength basis of the wear mechanism. During the wear process, residual tensile stresses of a plastic-destructive nature are formed on the working surface. Qualitatively, the patterns of changes in these stresses correlate with the patterns of the rheological-fatigue parameter and wear resistance. The influence of humidity on the formation of the rheological-fatigue parameter in soils of different mechanical composition is carried out mainly through fracture toughness, the size of the plastic zone in the vicinity of the crack tip and cyclic fracture toughness in the following dependencies: the higher the fracture toughness, the size of the plastic zone in the vicinity of the crack tip and The lower the cyclic fracture toughness, the greater the rheological-fatigue parameter of the steel.

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1. INTRODUCTION

Parts and tools made of low-alloy steels of soil-cultivating machines are operated when moving in a mass of loose abrasive particles - the soil - and wear out intensively, changing their shape and size. Therefore, they have to be replaced or repaired frequently.

The main agents of wear in such conditions are hard (HV 7-11 GPa) mineral particles of quartz, constituting approximately 75...85% of the soil. Most of the particles have a round shape and, as they move along the surface of the part, they occupy a more stable position in relation to it and to each other. Therefore, soil must be considered as a solid body with a very rough surface and a moving active layer [1].

When a part moves relative to such a solid body, each of its protrusions (abrasive particles) that interact with its surface simultaneously penetrates it and progressively moves along it, leaving a mark in the form of a mark or a scratch several millimeters long. As a result, the surface turns out to be covered with many marks and scratches identically oriented in the direction of movement, merging along the length and being the main sign of a high-quality wear pattern of the metal.

It is obvious that the mobility factor of the active layer in the adopted model of the soil environment contributes more to the deforming than to the micro-cutting action of abrasive particles. Therefore, the formation of marks and scratches on the wear surface occurs mainly as a result of the implementation of the processes of repeated deformation and low-cycle fatigue.

In addition, the worn surface has very smooth areas without oriented traces of deformation and microcutting.

Thus, when moving in the soil, abrasive wear of the metal is of a mixed nature and includes the following forms: mechanical, mechanical fatigue and mechanochemical. The leading role, in this case, is always played by the mechanical fatigue form, and the accompanying role is played by the mechanical and mechanochemical ones, the ranking of which is determined by the grade of steel and the mechanical composition of the soil [2].

The wear rate of machine parts and tools significantly depends on the technological properties, in particular, the abrasiveness and hardness of the soil.

The abrasiveness of the soil is manifested in the wear of the surface interacting with it when moving. The degree of abrasiveness is largely determined by the mechanical composition of the soil: it is higher in sandy soils and lower in clayey soils. Therefore, in clayey soils, the wear resistance of low-alloy steels is significantly higher (4….8 times) than in sandy soils [2].

Works [1,3] are devoted to studying the patterns of metal wear in soils of different mechanical compositions with changes in humidity. Experimental data have shown that with increasing humidity, the wear rate of steel varies within wide limits. However, this effect is explained in different ways. Thus, if in [3] it is associated with changes in the pattern of interaction between abrasive particles and the wear surface, caused by a decrease in soil hardness, then in [1] - the relationship between the simultaneous decrease in the strength of the abrasive and wear metal, caused by an increase in the speed of their relative sliding as the content increases moisture.

The interaction of all types of soil with a wear surface includes one common element: in each case, the separation of a wear particle from the surface is usually preceded by the process of fatigue failure of the metal. As a result of the implementation of this process, a specific structure of the surface layer is formed, which includes: the outer (cracked) layer, which contains the largest number of discontinuities in the form of microcracks or sources of their nucleation and obeys the laws of fracture mechanics, as well as the adjacent plastically deformed layer, which, in addition to the nonlinear effects accompanying discontinuities in the outer layer, contains a large number of different defects in the crystal structure of deformation origin - stripes and slip lines, twin fault lines, rotational deformation modes, etc. This structure indicates that two independent processes—deformation and destruction—occur simultaneously in the surface layer. In this case, destruction processes predominate in the outer layer, and deformation processes predominate in the adjacent layer. The relationship between these processes is established by the rheological-fatigue parameter, through which, in particular, the influence of the mechanical composition of the soil on fatigue failure, and, consequently, the wear resistance of low-alloy steels is controlled [2,4].

There are currently no studies of wear failure in soil environments with changes in humidity, which complicates the scientifically based choice of steel grade when designing machine parts and tools for soil-cultivating equipment with a high level of wear resistance and necessitates additional study of this issue.

The purpose of the work is to further study the patterns of destruction and wear resistance of low-alloy steel when moving in soils of different mechanical composition with changes in their moisture content.

2. PROBLEM STATEMENT

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The interaction of all types of soil with a wear surface includes one common element: in each case, the separation of a wear particle from the surface is usually preceded by the process of fatigue failure of the metal. As a result of the implementation of this process, a specific structure of the surface layer is formed, which includes: the outer (cracked) layer, which contains the largest number of discontinuities in the form of microcracks or sources of their nucleation and obeys the laws of fracture mechanics, as well as the adjacent plastically deformed layer, which, in addition to the nonlinear effects accompanying discontinuities in the outer layer, contains a large number of different defects in the crystal structure of deformation origin - stripes and slip lines, twin fault lines, rotational deformation modes, etc. This structure indicates that two independent processes—deformation and destruction—occur simultaneously in the surface layer. In this case, destruction processes predominate in the outer layer, and deformation processes predominate in the adjacent layer. The relationship between these processes is established by the rheological-fatigue parameter, through which, in particular, the influence of the mechanical composition of the soil on fatigue failure, and, consequently, the wear resistance of low-alloy steels is controlled [2,4].

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materials.

3. RESEARCH CONSIDERATIONS

The object of the study was structural low-alloy steel 65G, the chemical composition of which is given in Table 1

Table 1. Chemical composition of the investigated steel.

Brand steel	Content, %								
	C	Mn	Si	P	S	Cr	Ni	Cu	B
65G	0,65	1,11	0,27	0,035	0,035	0,25	0,25	0,22	-

Specimens from the specified steel were strengthened by heat treatment in the mode (Table 2).

The heating source was an electric muffle furnace SNOL7.2/1300 (NPP Termoinzhiniring, Kharkov).

Table 2. Mode of heat treatment of investigated steel.

Brand steel	Hardening			Vacation	
	Heating temperature, ℃	Duration of exposure, min.	Hardening medium	Heating temperature, ℃	Holding time, min.
65G	820	30	Oil	470	60

The strengthened samples were subjected to tensile, indentation, and soil friction wear tests.
Tensile tests were carried out using a universal machine UMM-50. As a result, a load diagram was obtained, from which the true deformation ε_{true} of the steel was determined.

Indentation tests were carried out using a universal hardness tester "NOVOTEST T-UD2" (LLC Scientific and Technical Center "Industrial Equipment and Technologies", Novomoskovsk). As a result, the Vickers hardness *HV* of the steel surface was determined in the initial state and after wear tests. The data obtained were used to assess the structural-phase state of steel based on residual stresses introduced into the friction surface [5].

Wear tests on steel during friction in the soil were carried out using the modernized "impeller" method on a testing facility [6], the diagram of which is shown in Fig. 1

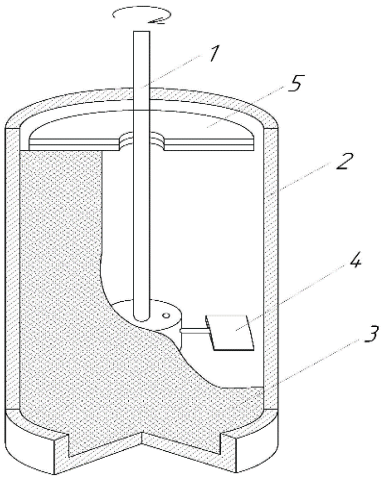


Fig. 1. Diagram of a setup for testing steel for wear when friction in soil: 1 - sample holder shaft; 2 - cylinder; 3 - soil; 4 - samples; 5 - mogosection disk.

The soil was a mixture of clay (particle size 0.1 - 1 μm) and sand (particle size 80 - 100 μm, hardness 9.8 - 12.7 GPa) in the ratios (Table 3).

Table 3. Soil types

Soil type	Clay content,%	Sand content, %
Sandy loam	15	85
Medium loam	35	65
Light clay	65	35

All types of soils were artificially moistened with distilled water in a ratio of 6%, 12% and 18% by weight of dry soil. After which, they were thoroughly mixed and kept for at least four hours for a more uniform distribution of moisture. Humidity before and after the experiment was determined by the gravimetric method by drying soil samples in an oven at a temperature of 105 ℃.

The essence of tribological tests consisted in the rotation of steel samples immersed in dry and moistened soils of the indicated types. Test mode: soil pressure on the samples P = 122.6 kPa, rotation speed of the samples V = 125.28 m/min, friction path of the samples L = 500 km. During the tests, the friction force F_{fr} was measured. The wear of samples G was determined by weighing on an electronic analytical balance CP 34001 S (Sartorius (Germany)). The measure of wear resistance ε was the reciprocal of abrasive wear.

The analysis of the mechanics of steel fracture during wear in the studied soils was carried out using the following characteristics: the critical stress intensity factor (fracture toughness) K_{1c}, the size of the region of inelastic relaxation processes in the vicinity of the crack tip h_p, the rheological parameter $R= K_{1c}/h_p^{½}$, cyclic strain viscosity $\Delta\varepsilon$, as well as true strain ε_{true}, which were determined by the methods described in [7 - 9]. These characteristics were used to calculate the rheological-fatigue parameter

$$R_f=R\,(\varepsilon_{true}/2\,\Delta\varepsilon)^2.$$

The results obtained during the research were processed by methods of mathematical statistics. In the absence of moisture, sandy loam soil particles, during movement, are in direct contact both with the wear surface and with each other, which contributes to the formation of an appropriate degree of their fixation. Due to the low thermal conductivity of dry soil, significant temperatures develop in the frictional contact zones of particles, promoting intense oxidation of the plastically deformed metal. As a result, layers of oxides are formed on the surface, which are subsequently carried away in the form of wear products, which indicates the predominance of mechanochemical destruction in its wear [10].

In the presence of water, adsorption molecular films are formed on the particles, which protect them from direct contact with each other and with the metal. In addition, wet soil has a higher thermal conductivity than dry soil, and therefore the temperatures in the frictional contact zones of the abrasive and metal will decrease.

Abrasive particles and metal under such conditions are characterized by an adsorption decrease in strength due to the internal Rehbinder effect [11]. The presence of an adsorption medium weakens the cutting action, and, consequently, reduces the abrasiveness of the particles, since when interacting with metal, their sharp corners and edges are easily destroyed. On the surface of a metal, an adsorption-active medium under repeated action of external forces facilitates the process of destruction, which negatively affects its wear resistance. However, an increase in thermal conductivity, a decrease in the abrasiveness of sandy loam particles and the strength of the metal occur simultaneously. The ultimate effect of these changes, as can be seen from the experimental data presented in Table 4, depends on the amount of aqueous medium.

hus, when humidity changes from 0 to 6%, the wear resistance of steel increases due to an increase in the thermal conductivity of sandy loam, a decrease in the degree of fixation of abrasive particles in it, and the predominance of an adsorption decrease in the strength of particles over a decrease in the strength of the metal. An increase in water content to 12% leads to the fact that the adsorption decrease in the strength of the metal affects it to a greater extent than the decrease in the strength of particles together with an increase in the thermal conductivity of the soil. The wedging effect of the adsorption layer in wedge-shaped microcracks under repeated loading plays a decisive role in the process of surface destruction of the wear body. As a result, at a sandy loam moisture content of 12%, a significant decrease in the wear resistance of steel is observed.

Table 4. Dependence of tribotechnical and rheological properties of steel on moisture content in different types of soil.

Brand steel	Soil type	Soil moisture, %	Wear resistance, $\varepsilon \times 10^{2}$,kg^{-1}	Rheological parameter, R, GPa	Rheological-fatigue parameter, R_f,TPa
65G	Sandy loam	0	0,69	3,92	546
		6	1,22	4,06	972
		12	0,9	4,08	720
		18	1,72	4,08	1350
	Medium loam	0	1,35	4,1	1090
		6	2,35	4,08	1850
		12	3,12	4,08	2530
		18	4,46	4,11	3730
	Light clay	0	5,1	4,1	4020
		6	3,12	4,1	4020
		12	5,1	4,1	4020
		18	5,1	4,1	4020

A further change in humidity from 12 to 18% entails a significant decrease in the hardness of sandy loam, as well as an increase in its thermal conductivity and a decrease in the degree of fixation of abrasive particles in it. With a decrease in soil hardness, favorable conditions are created for the implementation of, along with the internal, also external Rebinder effect on the wear surface. The consequence of this effect is an increase in plasticization of the surface layer due

to the activation of surface and subsurface sources of dislocations. The emission of dislocations contributes to the blunting of wedge-shaped surface cracks, thereby slowing down the process of surface destruction. This can explain the increase in wear resistance of steel at a humidity of 18%. In such conditions, pockets of corrosion are found on the wear surface.

In dry medium loam, the increased clay content, compared to sandy loam, increases its thermal conductivity and the degree of fixation of particles in it, and the reduced sand content reduces the number of abrasive particles, as a result of which the wear resistance of the metal increases.

In the presence of moisture, as its content increases, the thermal conductivity of the soil further increases. As a result of the combined action of clay and water, the contact zone cools more intensely than in sandy loam.

Due to the increase in the degree of fixation of abrasive particles, one could expect a corresponding decrease in the wear resistance of the metal [12]. However, experimental data showed the opposite pattern: with changes in humidity, wear resistance in medium loam turned out to be significantly higher than in sandy loam (Table 4). In addition to reducing the concentration of abrasive sand particles and the degree of their fixation, among the main reasons for achieving this result, one should note the predominance of the adsorption decrease in the strength of the abrasive over the adsorption decrease in the strength of the metal when the humidity changes from 0 to 6% and from 6 to 12%. When humidity increases to 18%, wear resistance is more affected by a decrease in the degree of particle fixation and adsorption plasticization of the metal.

n dry light clay the content of clay particles is higher and the content of sand is lower than in medium loam. Therefore, the thermal conductivity and degree of fixation of abrasive sand particles in it increases, and their quantity decreases, which leads to higher wear resistance of the metal.

The presence of moisture in such soil has virtually no effect on the wear resistance of the metal compared to dry soil. This indicates that the degree of fixation of abrasive particles in it remains unchanged, and adsorption phenomena in the abrasive and metal equally affect the destruction of the surface.

Thus, based on the fact that wear is of a fatigue nature, the influence of soil moisture on the wear resistance of steel is carried out by regulating active deformation and fatigue phenomena on the rubbing surface due to the simultaneous cooling, adsorption and physicochemical effects on the properties of the metal, soil and its abrasive particles. The gradually changing nature of the curves of the dependence of wear resistance on moisture with changes in the mechanical composition of the soil is determined by the relationships between the speeds and intensities of the indicated actions of water (Figure 2).

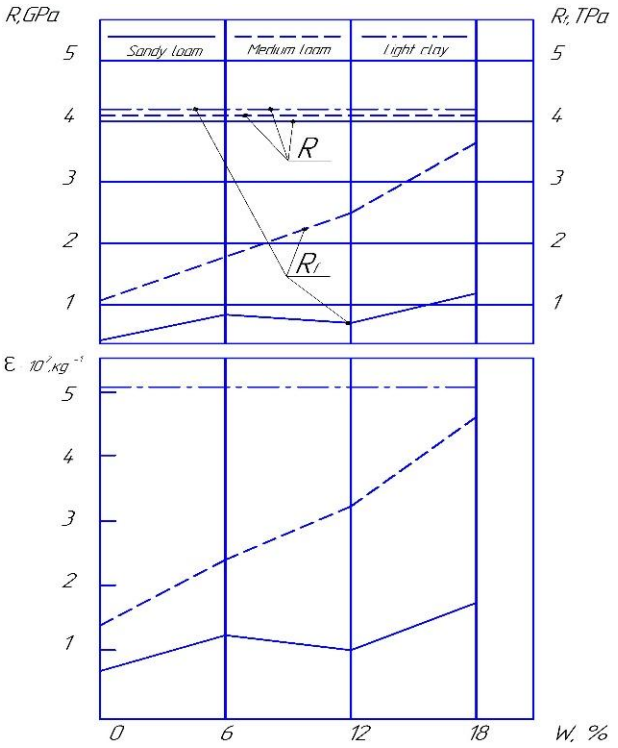


Fig. 2. Comparison of wear resistance *(ε)* with rheological parameter *(R)* and rheological-fatigue parameter *(R_f)* of steel after wear in soils of varying moisture content (*W).*

The same figure shows the results of determining the rheological properties of steel in the studied types of soil as their moisture content changes: the rheological parameter *R*, which characterizes the resistance to the initiation and development of lateral cracks under static load and is a criterion of wear resistance under conditions of abrasive wear, where the leading role in the damage of the surface layer is played by destruction processes

and the rheological-fatigue parameter R_f, characteristics of resistance to the initiation and development of lateral cracks under fatigue load, which is a criterion of wear resistance under conditions of abrasive wear, where the leading role is played by deformation processes.

A comparison shows that with changes in humidity, wear resistance in its tendency completely copies the course of the dependence of the rheological-fatigue parameter in all types of soil. This indicates the high sensitivity of wear resistance to the rheological-fatigue parameter. At the same time, such a pattern between the rheological parameter and wear resistance is observed only in light clay. Consequently, the influence of humidity on the formation of wear resistance in different types of soil is carried out through the rheological-fatigue parameter. Then, in the strength basis of the wear mechanism, the mechanical component of contact interaction should be considered decisive. Therefore, in order to take into account the effect of humidity on wear resistance in different types of soil, the choice of steel must be made based on its ranking according to the rheological-fatigue parameter.

During the wear process, residual tensile stresses of a plastic-destructive nature are formed on the working surface [13]. A comparison shows that with changes in humidity in all types of soil, the qualitative nature of the patterns of residual stresses $\sigma_{_res}$ (Figure 3), rheological-fatigue parameter R_f,and wear resistance ε (Figure 2) coincides, which is most clearly manifested in sandy loam soil. At the same time, the pattern of residual stresses in sandy loam is the main reason for the violation of the quantitative correspondence between these patterns. This can be explained by the increasing level of residual stresses due to the higher contribution of destruction processes to metal wear, due to the increased sand content compared to clay soils.

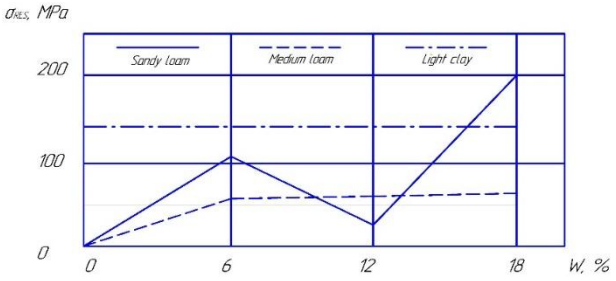


Fig. 3. Change in residual stresses *(σ_{res})* of steel after wear in soils of varying moisture content (*W).*

Since the rheological-fatigue parameter includes a number of physical and mechanical quantities, the patterns of their change are of scientific and practical interest, as well as the role of each of them in the formation of wear resistance of steel when the moisture content of the studied soils varies.

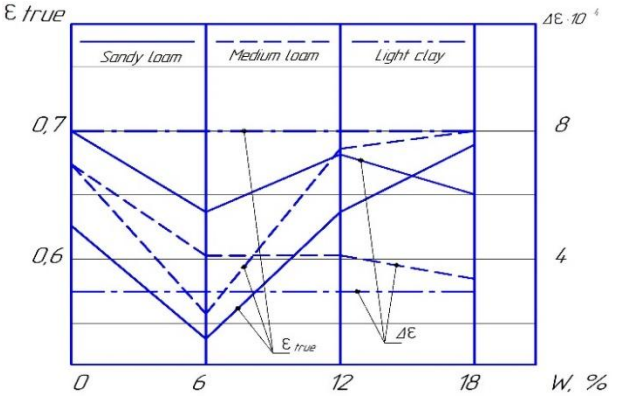


Fig. 4. Change in true deformation (ε_{true}) and cyclic strain viscosity *($\Delta\varepsilon$)* of steel after wear in soils of different moisture content (*W).*

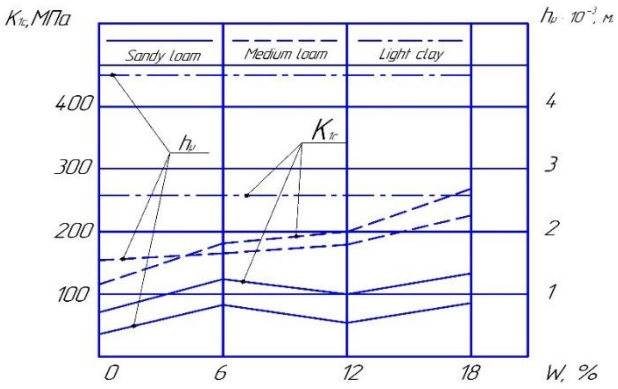


Fig. 5. Change in fracture toughness *(K_{1c})* and the size of the area of nonlinear effects in the vicinity of the crack *(hn)* steels after wear in soils of varying moisture content (*W).*

Figures 4 and 5 show the patterns of true deformation ε_{true} and cyclic strain viscosity $\Delta\varepsilon$ (Figure 4), fracture toughness K_{1c} and the size of the plastic zone in the vicinity of the crack tip h_p (Figure 5) of steel with changes in moisture content in soils of different mechanical compositions.

The analysis of these patterns was carried out on the basis that during cyclic deformation, the main stresses arise in the surface layer, which are caused by the external force of the abrasive. After the cessation of such exposure, they are removed. In addition to the main stresses, residual stresses

also arise in the metal due to the unevenness of its deformation. These stresses remain in the metal after the impact of the abrasive ceases. In the process of cyclic deformation of the surface layer, they are added to the main ones.

The resulting operating stresses, due to defects in the crystal lattice and a number of other inhomogeneities, contribute to the initiation of wedge-shaped microcracks in the surface layer. The tip of each microcrack is a source of dislocation emission, as a result of which a local plastic zone is formed in front of it. The propagation of such microcracks occurs as a result of the influence of residual stress fields.

A decrease in the strength, abrasiveness and degree of fixation of particles with a change in the humidity of sandy loam from 0 to 6% (see above) leads to a decrease in the resulting stresses due to a significant decrease in the main stresses, which in its magnitude, apparently, exceeds the observed increase in residual stresses in the metal (Figure 3). On the one hand, this entails a decrease in the true strain ε_{true} and cyclic strain viscosity $\Delta\varepsilon$ (Figure 4), and on the other hand, an increase in the size of the plastic zone at the crack tip h_p, contributing to the blunting of the latter, and, consequently, an increase in fracture toughness K_{1c}. (Figure 5).

In contrast, a further decrease in the degree of fixation of abrasive particles with an increase in the humidity of sandy loam from 6 to 12% (see above) contributes to an increase in the resulting stresses due to a significant increase in the main stresses, exceeding in magnitude the decrease in residual stresses (Figure 3). As a result, the true strain ε_{true} and cyclic strain viscosity $\Delta\varepsilon$ increase (Figure 4), and the size of the plastic zone at the crack tip h_p and fracture toughness K_{1c} decrease (Figure 5).

A change in the humidity of sandy loam from 12 to 18% is accompanied by a continuing decrease in the degree of fixation of abrasive particles, which leads to an increase in the resulting stresses in the surface layer of the metal due to a significant increase in residual stresses, which in magnitude exceeds the decrease in the main stresses (Figure 3). As a result, the true strain ε_{true} of steel increases (Figure 4), cyclic strain viscosity $\Delta\varepsilon$ decreases (Figure 4), and the size of the plastic zone at the crack tip h_p and fracture toughness K_{1c} increase (Figure 5).

In medium loam, the patterns of residual stress σ_{res} (Figure 3), true strain ε_{true} and cyclic strain viscosity $\Delta\varepsilon$ (Figure 4), fracture toughness K_{1c} and the size of the plastic zone in the vicinity of the crack tip h_p (Figure 5) of steel with changes in moisture content qualitatively coincide with similar patterns in sandy loam. However, there are significant quantitative differences between them, due to changes in the ratio of the contribution of the main and residual stresses to the destruction process, caused by a higher degree of fixation of abrasive particles in medium loam.

In light clay, the degree of fixation of abrasive particles is higher than in medium loam. Water does not have a significant effect on its value, and, consequently, the ratio of the contribution of the main and residual stresses to the destruction process. Therefore, with an increase in its content, the residual stresses σ_{res} (Figure 3), the true strain ε_{true} and the cyclic strain viscosity $\Delta\varepsilon$ (Figure 4), the fracture toughness K_{1c} and the size of the plastic zone in the vicinity of the crack tip h_p (Figure 5) of the steel practically do not change.

A comparison shows that as humidity increases, fracture toughness, the size of the plastic zone in the vicinity of the crack tip, and cyclic strain viscosity tend to quantitatively and qualitatively copy the course of the rheological-fatigue parameter dependence in all types of soil. This indicates the high sensitivity of these quantities to the rheological-fatigue parameter under the conditions under consideration. At the same time, between residual stresses and the rheological-fatigue parameter, such a pattern is observed only in qualitative terms. Consequently, the influence of humidity on the formation of the rheological-fatigue parameter in different types of soil is carried out mainly. through fracture toughness, the size of the plastic zone in the vicinity of the crack tip and cyclic strain viscosity.

4. CONCLUSION

1. When moving in soils of different moisture content, a mechanochemical form of abrasive wear is realized on the friction surface of low-alloy steel.

2. The role of water in the formation of wear resistance is to regulate active deformation and fatigue phenomena on the friction surface through its simultaneous cooling, adsorption and physical-mechanical effects on the properties of metal, soil and abrasive particles. The nature of the dependence of wear resistance on moisture with changes in the mechanical composition of the soil is determined by the relationships between the rates and intensities of the indicated effects of water.
3. The influence of humidity on wear resistance in soils of different mechanical composition is carried out through the rheological-fatigue parameter in the following dependence: the greater the rheological-fatigue parameter, the higher the wear resistance of the steel. Based on this, the mechanical component of contact interaction should be recognized as determining the strength basis of the wear mechanism. Therefore, when choosing a grade of low-alloy steel for the manufacture of machine parts and tools operating in wet soils of different mechanical composition, one should be guided by its ranking according to the rheological-fatigue parameter
4. During the wear process, residual tensile stresses of a plastic-destructive nature are formed on the working surface. Qualitatively, the patterns of changes in these stresses correlate with the patterns of the rheological-fatigue parameter and wear resistance. It is most clearly manifested in sandy loam soil, where residual stresses, caused by an increase in the contribution of destruction processes to metal wear, are the main reason for the violation of the quantitative correspondence between these patterns.
5. The influence of humidity on the formation of the rheological-fatigue parameter in soils of different mechanical composition is carried out mainly through fracture toughness, the size of the plastic zone in the vicinity of the crack tip and cyclic strain viscosity in the following dependencies: the higher the fracture toughness, the size of the plastic zone in the vicinity of the crack tip cracks and the lower the cyclic strain viscosity, the greater the rheological-fatigue parameter of the steel.

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