The information-physical mechanism of diagnostic of the functional coatings erosive wear by water jet

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Abstract. This paper discusses process of the functional coatings erosive wear by water jet with the purpose of coatings quality characteristics diagnosing. The probabilistic model of this process is considered. The main model feature is the surface and volume damages analysis after water jet influence. The experiments show the directly dependence between these coatings damages types. This fact highlights the water jet diagnostic efficiency.

Keywords: functional coating, water jet influence, erosive wear, probabilistic model.

1. Introduction
Successful development of engineering surfaces for critical products, mainly in the field of technological quality assurance of various functional coatings requires the creation of a physically adequate apparatus for their control and express diagnostics. Expert-analytical analysis showed [1–4] that ultra-jet hydrodiagnostics (UJD) has the greatest performance potential. Technologically, the UJD is based on an assessment of the degree of influence of the quality parameters of the surface layer of the object of study on the information-physical characteristics of its local hydroelectric destruction process under the action of a high-speed ultrajet fluid (water), with a power flux density of more than 0.1 MW/mm². This situation is explained by the fact that under ultrajet impact in the surface layer there is a stress-strain state (SSS) of the material, which is model-like for most practically important cases during its operation: friction, variable power loads, etc. Therefore, the UJD has certain informational advantages compared to the diagnostics of the quality of the surface layer through the use of an air-abrasive or hydro-abrasive jet, as the main tool of the physical-technological implementation, operating-simulated SSS.

2. Formulation of the problem
This problem consists of the analysis of the correlation of the two main components of the process of ultra-jet hydro erosion of the surface layer of the product being diagnosed:
- Variable wedging action of high (P > 100 MPa) water pressure (UJ) on the kinetics of nucleation, development and fusion of surface crack-like micro- and macro-defects between themselves and underlying similar discontinuities in the subsurface layer;
- Formation by the classical fatigue mechanism of critical values of crack-related damage to the material of the surface layers of the object of diagnosis in the context of intense variations of its SSS, characteristic of the hydrodynamic effects of high-speed UJ.

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Note that the distinction between the significance of the surface-proppant and volume-fatigue mechanisms of ultrahydro-erosion material, schematically depicted in Fig. 1 for most operating ultrajetting technologies (UJT) is mainly of scientific and methodological value, in particular, in the UJ-cutting of sheet materials.

Figure 1. Hydrodynamic picture of the occurrence, development and merging of discontinuities in the surface layer of the object of analysis - the mechanism of its hydroelectric UHJ destruction.

In Figure 1:
1 - diagnostic ultra-hydrojet incident on the surface of the object of analysis (UHJ) with a speed Vc, which creates a hydrodynamic pressure P-var in the process of braking in the zone of the UJ-impact;
2 - hydraulic jets, reflected and having a speed Vort from the surface of the object of analysis, and hydro cavity formed under UHJ;
3 - functional coating applied to the surface of the object of analysis;
4 - source material of the object of analysis;
5 - micro nesting (micro and submicrocracks) in the structure of the functional coating 3;
6 - micro-continuity (micro- and submicrocracks) in the starting material of the object of analysis;
7 - technological potentially dangerous defects in the surface layer of the object of analysis;
8 - crack-like initial, nascent and developing defects at the interface between the surface of the object of analysis and its functional coating;
9 - existing, incipient and developing microcracks (defects, discontinuities) on the surface of a functional coating under the variable effect of hydraulic pressure P;
10 - existing, incipient and developing microcracks (defects, discontinuities) on the free surface of the hydrodynamic contact between the object of analysis and the inhibited UHJ;
11 - contours of the dispersible UHJ particles from the surface of the functional coating 3;
12 - the contours of the dispersible UHJ of the solid-phase particles from the surface layer of the object of analysis;
13 - microrelief $R_K$ and topography (depth $h_k$) of surface hydro cavity, formed in the process of diagnosing UHJ;
14 — elastic deformation waves — acoustic emission waves (AE) generated in the material of the object of analysis by the hydrodynamic interaction of the UHJ with its solid-state surface;
15 - AE waves propagating through the body of the UHJ from the zone of its shock-dynamic interaction with the surface of the object of analysis.

However, in the case of UJD of functional coatings, the role of each of these mechanisms is directly related to the informative performance of the entire procedure for express analysis of their operational quality. This is explained by the fact that the first “wedging mechanism” of the diagnostic factor of ultra-jet impact is closely related to the “micro and sub microefficiency” of the functional coating itself. This component of the quality of the coating manifests itself in the form of the ability to withstand operational loads, leading to a violation of its continuity and an increase in damage, mainly during friction-force contact of structural elements in friction units, working surfaces of cutting tools, etc.

The second, no less significant mechanism of fatigue damage accumulation in the subsurface layer of the substrate material is physically responsible for the ultrahydro erosion local microfragmentation of the surface layer of the object of diagnostic exposure to UJ and, most importantly, damage to its interface with functional coating. It is the kinetics of this process that very often determines the technological quality of the functional coating, which consists in ensuring high values of the adhesive interaction between it and the underlying, protected layers of the main structural material of the product. Therefore, a detailed analysis of the coating peeling parameters during UJD is an information-significant sign of its operational and technological quality. This circumstance allows you to quickly work out the rational modes of formation of various modes of formation of various functional coatings without conducting time-consuming and expensive full-scale experimental studies, as well as carry out current, for example, selective or 100% control of the stability of the technology for their production. Moreover, with a 100% control, the UJ is applied to the contact-inoperative coverage area, for example, at a certain distance of their cutting edges of the forming tool.

Note that, if necessary, it is possible to quickly obtain information about the abrasive resistance of functional coatings by introducing highly hard particles into the UJ, for example, in the form of fine silicon carbide, aluminum oxide (corundum), etc.

Thus, the UJD by applying the fluid UJ (water) or high-speed jet of the corresponding abrasive-liquid suspension is an effective tool for the rapid analysis of the qualities of the most diverse functional coatings and methods of physical and technological hardening of the surface layer of product parts.

3. Analytical studies

To formalize the role of the surface wedging and volume fatigue mechanisms of erosive destruction of the surface layer of the coated material, we use the probabilistic approach, which is due to the specific variety of interaction processes of the characteristic physical and technological factors of the UJD operation. Moreover, in a deterministic formulation, the solution of this problem, taking into account the scale factor of strength of solids, can in principle be found using the well-known surface fracture modeling apparatus proposed, for example, in [5–6].
Taking into account the parallel processes of the formation of surface and subsurface crack-like damage to the material area being analyzed, the probabilistic distribution of microdefects, reflecting the large-scale microdestruction, based on the dependencies obtained in [7–8], we can write the total initial probability ratio in the form:

\[ P_c(t) = P_S + P_V - P_S P_V \]  

where: \( P_c \) is the total probability of destruction and separation at the current time of analysis \( t \) of the considered fragment (microparticle) of the surface material under hydrodynamic effects of UJ; \( P_S \) and \( P_V \) – respectively, the probability of the processes of surface and (\( S \)) bulk (\( V \)) local fragmentation (microfracture, dispersion), material in the impact zone of UJ. Physically \( P_c \) means the ratio of dispersed particles destroyed at the moment of time \( t \) to the maximum possible amount.

Using, after appropriate functional and physical adaptation, the results of the theoretical analysis performed in [9] \( P_S \) and \( P_V \) can be defined as:

\[ P_S(t) = 1 - \exp\left[-\int_0^t c_S k_S(\tau) d\tau\right] \]  

\[ P_V(t) = 1 - \exp\left[-\int_0^t c_V k_V(\tau) d\tau\right] \]

where: \( c_S(\tau) \) and \( c_V(\tau) \) – accordingly, the concentration of microdefects, for example, subcritical cracks on the surface of the applied coating (\( S \)) and in the subsurface layer (\( V \)), as shown in Fig. 1; \( k_S \) and \( k_V \) – are respectively variable parameters, functionally determining the effects of SSS on the formation kinetics of \( c_S \) and \( c_V \).

In fact, (1) determines the total probability of surface and subsurface hydro erosion fragmentation of the surface layer of the object of analysis, and (2) and (3) describe the kinetics of their change during the UJD, and in latent form these relations are functions of the coordinates included in the structure of \( c_S \) and \( c_V \).

Considering in the first approximation that \( c_S \) and \( c_V \) are characterized by some averaged quasi-constant values, and the intensity of the local erosional fragmentation of the material over time is much less than the frequency of the variable-wave change of its SSS under the hydrodynamic action of the UJ ratio (1) with (2) and (3) for small \( c_S \) and \( c_V \) will look like:

\[ P_c \sim k_S c_S + k_V c_V \]

Thus, (4) is a functional interpretation of the independence of the change in the crack-like defects of the surface of the functional coating and the subsurface layer of the substrate material under the hydrodynamic effects of the UJ in the process of implementing the UJD operation. Physically (4) reflects the principle of linear summation of damage, known in the mechanics of fracture as the Bailey principle. Moreover, due to the smallness of the critical values \( c_S(l) \) and \( c_V(l) \), where \( l \) is the length of the crack-like defect close to the critical value, the law of rare events is valid - Poisson’s law, functionally similar to the exponential term in (2) or (3) describing the law of sudden failures, which governs the kinetics of the processes of variable-nonstationary erosion fragmentation of the surface layer of a material under shock-wave hydrodynamic effects.

It should be emphasized that from the scientific and applied point of view, the linear relationship of type (4) allows direct experimental verification by varying the values of \( S \) and \( cV \) with all other conditions being equal, UJ-interactions.

4. Experimental results

We illustrate the above with the results of direct experiments on the UJD of functional coatings, the main methodological feature of which was the functionally independent change of \( cS \) and \( cV \) by special physical and technological methods.
At the first stage of the experiments, five samples of steel X18H10T were subjected to fatigue loading with a different number of cycles of force action on them. This led to varying degrees of damage to their material, the appearance and development of crack-like submicro- and microdefects on the surface and in the thickness of the samples. Then, the surface of the samples was subjected to scribing UJ-effect on the FLOW standard hydraulic unit at a working pressure of $P = 420$ MPa. As a result, hydro cavities were formed on the surface of the tested samples, the depth of which $h_k$ completely correlated with the normalized maximum value with the number of cycles of their previous fatigue loading:

$$h_k = k_c \overline{N} \sim 0.5\overline{N}$$  \hspace{1cm} (5)

where:

$h_k = h_{ki} / h_{\text{max}}$ – normalized to the maximum value depth of the hydro cavity formed by the UJ on the surface of the $i$ –th sample ($i = 1.2 ... 5$); $h_{\text{max}} \sim 3.50$ mm – the maximum value of the hydro cavity on the 5th sample, which turned out to be in this case the maximum number of loading cycles on a specially created test-process unit ($N_{\text{max}} = 50 \cdot 10^3$ cycles); $k_c$ – experimental coefficient of proportionality between the degree of damage ($N$) and its ability to resist; UJ - destruction, which is characterized by the value of $h_k$.

In this case, $k_c \sim 0.5$. The obtained experimental results are presented in Fig. 2

![Figure 2](image)

**Figure 2.** Experimental determination of the shielding effect of the coating on the surface of the UJS-hydroerosion.

In Figure 2:
1 - intensity of locally-surface hydroerosion UJ-destruction of samples subjected to various levels of fatigue-force loading;
2 - intensity of hydroerosion of samples, after applying a functional coating of TiN on their surface.

Note that the linear functional dependence of the type (5) has a completely independent information and diagnostic value, which was described in detail in [10], dedicated to the physical and technological capabilities of the UJD. Moreover, some decrease in $h_k$ when $i = 2$, i.e. the second test specimen showed
a slight increase in hydroerosion resistance, apparently due to the presence of a plastic hardening factor for the test material at N~104 loading cycles.
Thus, at the initial stage of the experiments, the variability of the parameters c_s and c_V was realized, due to the different degrees of fatigue damage of the diagnosed samples. In this case, this circumstance is described by the functional dependence of the type (5) reflecting the degree of hydro erosion, UJ impact on the material with different levels of the initial crack-like defects.
Then, a functional protective TiN coating was applied to the surface of all samples on a standard ion-plasma unit. This coating, according to the above description of 2 types of hydro erosion fracture mechanism, would have to screen the role of the surface - “wedging” effect of water pressure in the braking zone of the UJD. Direct experiments on single-time UJ-scribing of the surface of all samples with very different degrees of initial damage showed an almost identical, insignificant degree of their hydro-erosion destruction, mainly due to local-plastic displacement of material from the UJ-impact zone (hk <0.1). This experimental result makes it possible to recognize the methodically valid physically conditional gradation of the UJ-hydro-erosion mechanism of the material into two, basically, interrelated processes, due to differences in the kinetics of c_S and c_V, formation described by the probabilistic relations (1) - (3) and their actually determined type of linearization (4).
It must be emphasized that in addition to the scientific value, the results presented in Fig. 2 may have serious technological application. Indeed, the targeted implementation of the shielding effect of the negative impact on the fatigue failure mechanism of the structural material of its surface defects by periodically applying a protective functional coating can be considered as a promising component of the renovation technology apparatus. This technology, based on the screening of the negative impact on the resource of fatigue failure of a construction of cracks emerging on its surface — initiating accumulations of dislocations, slip lines, etc., of micro- and sub-microdefects, is designed, along with thermo-gas-static and electropulse “healing” of structural micro-inhomogeneities, to reduce operational damage to the object of analysis. Moreover, only the exposure of the test sample in the working chamber of the ion-plasma unit, without coating, does not have practically significant effectiveness of shielding the effect of surface and bulk microdefects on the kinetics of the subsequent UJ-destruction of the test surface. The final series of experiments consisted in artificially increasing the value c_s, ceteris paribus, by scribing a diamond indenter with a different degree of graininess of the surface of samples with a TiN coating. The results of the subsequent UJ-impact presented in Fig. 3 showed:
- Close correlation between c_s and the intensity of the hydroerosion process, which confirms the validity of the hypothesis about the physiotechnological dualism of the UJ-surface destruction mechanism;
- equidistant-delayed nature of dependencies h_k=f(t) due to the lack of influence of the functional coating after its dispersion in the zone of UJ-exposure;
erosion-high significance of the functional coating at the initial stage of the UJ-impact, even in the conditions of its preliminary discrete damage (see items 2 and 3 in Fig. 3).
In Figure 3 it is accepted:
1 - the original sample without coating;
2 - coating with frequent deep scratches;
3 - coating with rare shallow scratches;
4 - intact functional coating.

Note that by means of a specially implemented coating mode with low adhesion to the substrate, the principal possibility of ultra-jet express control was established using UJ of this most important physical and technological parameter determining the performance quality of virtually all types of functional protective coatings. In this case, there was a film detachment of the functional coating under the action of an UJ, practically without finely dispersed hydrodynamic dispersion of the material of the surface layer.

Summarizing the above, it is possible to draw certain conclusions and outline the prospects for the further development of research results.
1. Ultra-jet diagnostics allows to solve not only practical tasks of express control of the quality of functional coatings, but also allows more detailed study of the specifics of the mechanisms of surface hydroerosion destruction in physically extreme conditions of the physic-energy UJ-effects on the material of a solid-state object of study.
2. Experimental testing and methodical specification of algorithms for modeling the process of UJ-diagnosing the quality of functional coatings will allow to obtain numerical values of the parameters necessary for reliable calculations of the resource and operational characteristics of various products and, above all, their functional contact working surfaces.
3. The development of a physical and mathematical analysis of the problem of UJ-interactions, in particular, full-scale implementation of the procedure of simulation-probabilistic modeling and / or building finite-element models of UJ-hydroerosion, supplemented by the results of field experiments, will create an effective system for predicting and verifying the potential impact of promising functional
coatings and technologies for their production, including those with gradient coatings of nano-compositional structure.

5. Conclusions
Taking into account the scientific and applied value and the variability of the technological capabilities of ultra-jet hydrophysical diagnostics and quality control of various functional coatings, their technical totality can be classified as a minimally invasive express method for obtaining objective information about the state parameters of the surface layer of the object of analysis, complementing the modern apparatus and surface engineering tools.

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