Express ultra-jet diagnostics of defect resistance for surface layer of a material

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Abstract. In the manufacture of products of modern technology, such technologies of waterjet processing as water jet cutting are successfully used for cutting materials. However, the physical and energy basis of ultrajet technology predetermines a much broader scope of its practical applications. Most of modern technical products are made of composite materials. Moreover, some of them were obtained by innovative methods, for instance, selective laser fusion, which complicates their diagnostics. This article proposes an innovative method for determining a new informative parameter characterizing the defect resistance of various materials. This technique is based on the process of hydro-erosive destruction in the process of ultrajet exposure to a high-energy jet on the surface of the material being diagnosed. Ultra-jet diagnostics (UJD) is based on the analysis of the dependence of the characteristics of local hydro-erosion of the diagnosed area of the surface of the object under analysis (OA) on the parameters of its quality. Surface quality parameters include physical and mechanical properties (PMP) and the degree of operational and technological damage. In this article a new formula has been developed that numerically determines the degree of defect resistance of materials. Experimental testing of this technique on some types of modern materials confirms its reliability. The directions of the future development of the research results are formulated.

1. Introduction

Nowadays the development of new models for assessing the operational properties, including the durability, of modern engineering components is one of the most urgent problems of mechanical engineering [1-3]. The additional informational and physical parameters may be required for estimation of the operational properties, primarily related to surface layer of products made of new materials. The dynamic defect resistance or damage under unsteady loading conditions should be attributed among these parameters. It was shown in [4–8] that by analysing the results of exposure to the surface of the investigated material with high-speed Ultra-Jet (UJ), express determination of not only changes in traditional Physical and Mechanical Properties (PMP) and parameters of the surface layer, but also an estimation of their defect resistance is possible. This estimation is carried out on the basis of comparison of informative signs related to local hydro-erosive destruction: the depth of the formed UJ hydro-cavern, the micro-relief of the surface structure, the mass-geometric parameters of eroded particles, etc. [9-11].

Defect resistance is not only about strength, stiffness or fatigue strength, but it is about all of them in complex. The simplicity of the technology for the implementation of method for its determination, as well as high productivity due to the speed of action of the UJ on the surface of the diagnosed part, allows quite justifiably to call this method an express diagnostic method.
2. Ultra-Jet Diagnostics Concept

Ultra-Jet Diagnostics (UJD) is a set of methods and means for creating the implementation of such parameters of a high-energy compact liquid jet, which, when it interacts with a diagnosed medium, for example, during shock-dynamic braking on a solid target, can lead to fixed purposeful changes in the processed material and/or in the liquid itself. In this case, a high-energy compact jet of liquid will be called an Ultra-Jet. And the resulting depression in the surface of the material as a result of UJD is hydro-cavern (or just cavern) [12]. Figure 1 depicts hydro-caverns of two different types of materials: abrasive material (Figure 1 a-b) and polymer material (Figure 1 c-d). Photos were taken with an electronic magnifier at 60x magnification. In other words, the hydro-cavern is like a scratch on the surface of the material made by high speed water jet and is referred to as an “Ultra-Jet”.

![Figure 1](image)

**Figure 1.** Illustrations of hydro-caverns of different types of materials:
(a) – top view of a hydro-cavern of abrasive material  
(b) – side view of a hydro-cavern of abrasive material  
(c) – top view of a hydro-cavern of polymer material  
(d) – side view of a hydro-cavern of polymer material.

3. Classic UJD Algorithm

The classic UJD algorithm, according to [12], includes the following steps:

1. The diagnosed surface is exposed to a hydro-jetting effect, which causes hydro-erosion of the surface under certain conditions (working pressure of the jet, its diameter, motion kinematics, etc.)
2. Then the parameters of hydro-erosion (particle size of the material, the structure of the material in the place of cut, depth of cut, etc.) are investigated and compared with the reference characteristics or with each other on different parts of the surface.
3. The obtained difference in the results of comparisons (absolute and/or relative) is used to judge the quality (resource, physical and mechanical properties) of the controlled area of the surface and the current state as a whole.

4. Suggested diagnostic technique

To increase the identification capabilities of UJ, the following physical and technological technique is proposed. At the first stage, the high-pressured hydro-UJ, which, according to the mechanisms of erosion destruction, carries out softening of its surface layer structure (loss of strength, weakening), is applied to the surface layer of the diagnosed Object of Analysis (AO), i.e. forms a sufficiently significant defect damage mainly in the form of a combination of micro- and nano-cracks.

On the second stage, following the previous UJ’s action trail, the impact is affected by hydro-abrasive-UJ. Moreover, the effect of its impact will depend not only on hydro-abrasive (micro-fatigue) resistance, according to [13], but also on the degree of previous softening of the surface layer of high-pressure hydro-UJ.

Further, the intact AO’s surface layer is exposed to a hydro-abrasive-UJ and the depth of the formed cavern is fixed. It is obvious that the difference between the depths of hydro-abrasive caverns will
characterize the defect resistance of the studied material under conditions of energy-extreme hydrodynamic effects on it.

As the first stage of UJD influences the internal and surface structure of the diagnosed material, the new parameter of defect resistance characterizes not only resistance of surface defects but also defects which are close to the surface but hidden in the material structure.

To increase the generality of the obtained comparison results, one can also give additional UJ actions, which follow the hydro-abrasive operation. Schematically, the foregoing is shown in Figure 2.

![Figure 2](image)

Legend:
1 – diagnostic hydro-UJ
2 – diagnostic hydro-abrasive-UJ
3 – hydro-cavern formed as a result of the first stage of diagnosis
4 – hydro-cavern formed as a result of the second stage of diagnosis

H1 – cavern depth, formed by the action of hydro-abrasive control system as a result of the 1st stage
H2 – cavern depth, formed by the action of hydro-abrasive control system as a result of the 2nd stage
HWJ – cavern depth formed by the influence of hydro-UJ at the 1st stage of diagnosis
h_wj – surface layer thickness, softened by the action of hydro-UJ
h_aj – surface layer thickness, softened by the action of hydro-abrasive-UJ

ΔH – difference between the results of hydro-abrasive actions of the 1st and 2nd stages

Figure 2. UJD implementation scheme: (a) - the 1st stage, (b) - the 2nd stage.

For the mathematical formalization of the foregoing, the following reasoning was carried out. The larger the ΔH value is, the less defect resistance the AO’s material has. From a physical point of view, this fact is explained by that after the first operation of hydro-UJ exposure at the 1st stage of diagnosis, the OA’s surface layer underwent significant softening, which in turn increased the efficiency of the subsequent hydro-abrasive-UJ exposure. The softening of the surface layer takes place due to the predominance of the influence of the low-cycle fatigue mechanism during the operation of hydro-UJ exposure [14].

At the 2nd stage of diagnosis, the AO’s surface was not subjected to preliminary hydro-UJ impact before exposure to hydro-abrasive-UJ, in contrast to the 1st stage, which allows us to consider it as not softened. In order to assess the degree of influence of studied material’s softening, we introduce the following formula defining a new property of defect resistance:
\[
\bar{D} = 1 - \frac{H_1 - H_2}{H_2}
\]  

(1)

where: \(H_1, H_2\) – the depths of hydro-cavern after the first and second stages of UJ action onto the surface of the material, mm.

Thus, analysis of the results of successive UJ’s impacts makes it possible to single out a new property of materials that are prone to damage of their surface layer under conditions of energy-extreme non-stationary loading, which is commonly to aviation and other similar industries.

It’s a remarkable thing that angle alpha (Figure 2) can significantly affect the cavern depth. The most powerful UJ impact is achieved when angle alpha is 45°, which was shown in [7, 10]. While the time of UJ’s action does not play a significant role. Obviously, the longer the exposure time, the deeper the cavern. However, in our case, the presence of a fast UJ’s action is enough.

5. **Experimental testing**

Table 1 is shown as an example of the implementation of the abovementioned. Table 1 in generalized form presents materials of UJD for three characteristic representatives of structural materials: high-strength steel RN13-8Mo (HRC=40-50); aluminium lithium alloy V-1469; ceramics based on \(\text{AL}_2\text{O}_3\) named VO-13; a sample obtained by selective laser fusion (SLF) from brand titanium powder TPP-1 and carbon fibre USAP-AF-LU-V.

| Material               | Identification mark | \(\bar{D}, [\%]\) |
|------------------------|---------------------|-------------------|
| Steel                  | RN13-8Mo            | 100               |
| Aluminum               | V-1469              | 94                |
| Ceramics               | VO-13               | 79                |
| SLF of Ti powder       | TPP-1               | 70-76             |
| Carbon fiber           | USAP-AF-LU-V        | 45-60             |

*The parameters variety for some materials takes place due to the significance of the anisotropy factor of the AO’s PMP.

6. **Discussion**

All in all there were examined for three samples per each type of the diagnosed material. The table 1 shows the average values. The spread of values was less than 5%.

The most defect-resistant material was steel, which confirms its low tendency to softening. Aluminium and ceramics have a lower defect resistance than steel, which is due to the inhomogeneity of their internal structure.

A consequence of the brittleness of ceramics is a significant statistical spread in the values of its strength in comparison with the spread in the strength of metallic structural materials. This is due to the high sensitivity of ceramics to the stress concentration created by defects in the microstructure (pores, inclusions) due to the difficulty of relaxation processes through plastic deformation [15].

TPP-1 and carbon fibre turned out to be the least defect-resistant materials, which is confirmed by the high porosity of these materials, as well as the anisotropy of their properties.

The construction of an empirical dependence of the concentration of defects on their size, as well as the determination of the influence of the concentration of defects of various sizes on the strength of products made of modern materials is an urgent issue [5, 15]. The development of methods for solving these problems could significantly improve the reliability of the proposed method for determining the defect resistance of materials.
7. Conclusion
Based on the results of this study, the following conclusions can be drawn:

1. The fundamental possibility of identifying the tendency of the studied materials to weaken their surface layer under hydrodynamic effects is shown.
2. It was established that, high-strength steel has the maximum defect resistance, and the carbon fiber composite material has the minimum. In this case, a reliable estimation of the surface layer PMP anisotropy is realistic.

The prospects for the development of research are the following, in addition to expanding the range of diagnosed materials:

1. To develop a full-scale model that allows to characterize the defect resistance of the material quantitatively by comparing the results of exposure by at least two hydrodynamic effects.
2. Carrying out the UJD operation under changing conditions, in particular during the quality diagnostics of complex-profile parts surface.
3. The estimation of the materials defect resistance or their damage in other types of test and diagnostic impact on them.

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