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Hydroerosion probabilistic modeling during surface layer quality ultrajet mesodiagnostics of aviation, rocket, and space equipment

A. Galinovskiy[1*], *A.* Barzov[1], *M.* Yanko[1], and *M.* Glotova[1]

[1]Bauman Moscow State Technical University (BMSTU), 2nd Baumanskaya Str., bldg. 1, 105005, Moscow, Russian Federation

Abstracts. At present, deterministic approaches to the hydroerosion processes modeling, which is the informative-physical basis of ultrajet mesodiagnostics (UJM), significantly prevail over other methods of analysis. This contradicts the probabilistic nature of local hydroerosion, which is caused by the formation of an array of eroded particles with highly variable mass-geometric parameters reflecting the realities of the initial microdefects distribution in the surface layer of the analyzed object (OA). Therefore, probabilistic modeling is a physically more reasonable tool for describing multi-factor processes in the ultrajet interactions zone, including the peculiarities of ultrajet hydroerosion. Hence, this paper proposes a probabilistic approach to modeling the process of hydroerosion damage, based on the separation of the particle from the material surface as a result of the interaction of necessary and sufficient conditions for dispersion. The obtained calculation data (probabilistic analysis) are close to the results of live experiments, which, in turn, allows recommending this approach of mathematical formalization of the minimally invasive quality control method using complicated configuration parts surface properties ultrajet mesodiagnostics, and also OA produced from anisotropic materials, widely used in aviation, rocket, and space technology.

1 Introduction

Methods of ultrajet treatment of materials are widely used in modern manufacturing technologies [1-3]. Informative-physical basis of ultrajet diagnostic (UJD) technology is the erosion process of analyzed object surface layer material by the action of high-speed hydrojet. Diagnostic features - first of all, shape and sizes of hydro-cavity, as well as mass-geometric parameters of eroded particles - uniquely correspond to operational and technological characteristics of surface functional quality of the most different OAs [4-6], mainly of critical items such as systems of aviation and/or rocket-space equipment.

Bauman Moscow State Technical University (BMSTU) SM12 Department suggested deterministic (including finite-element) models describing parameters of hydro-cavities formed because of ultrajet impact (UJI) on the surface of different OAs. The results of

* Corresponding author: galcomputer@mail.ru

modeling (combined with a set of direct experiments) allowed to substantiate the scientific and applied significance of the developed ultrajet mesodiagnostic (UJM) technology [7]. However, the mathematical dependencies of the already proposed the UJI analysis methods [8-10], including the UJM, are based on an integral approach to determining the diagnostic parameters of hydroerosion, first of all, the size and shape of hydro-cavities. This situation does not allow taking into account the probabilistic nature of formation of a set of discrete particles detaching from the material because of the ultrajet impact. These particles have a high potential of physically determined informativity.

2 Probabilistic modeling

Analysis of the physical essence of the ultrajet hydroerosion process has shown the necessity of building its probabilistic model with the following distinctive features. Both surface and subsurface defects of the diagnosed material reach critical values during ultrajet action. This process is accompanied by formation of erosion particles.

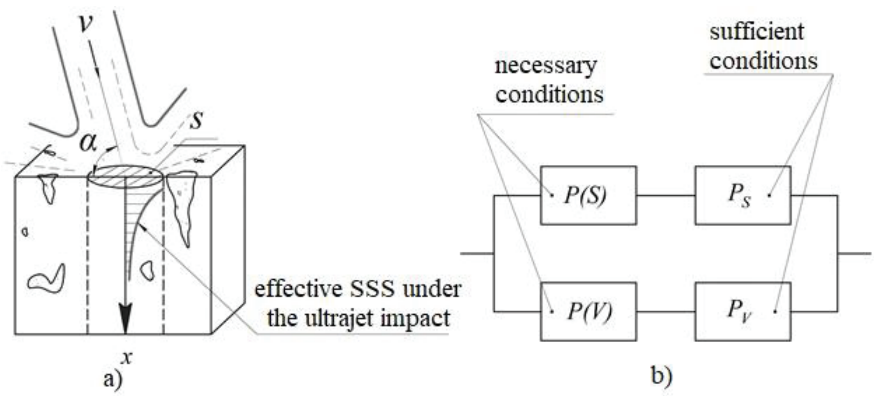

Fig. 1. a - structural diagram of the ultrajet impact on the initial microdefects and the pulse triggering their critical growth; b - structural diagram of the probabilistic interaction of necessary and sufficient conditions for the formation of an ultrajet-eroded particle.

According to the physically justified logic of the study [11], as well as other studies in the field of statistical fracture mechanics [12], it is not difficult to show that according to the calculation model in Fig. 1a, the probabilities of material particle eroding processes are described by the formulas:

$$P(s) = 1 - e^{(-C_S \cdot s)} \tag{1}$$

$$P(v) = 1 - e^{(-C_V \cdot s \cdot x)} \tag{2}$$

where P(S) and P(V) – probabilities of potentially dangerous defect presence in the area s and in a subsurface small bulk volume $V = s \cdot x$; S – effective erosion-forming area of ultrajet interaction with the diagnosed surface, respectively; C_S and C_V – mean values of erosion-dangerous defects concentration on the surface and in a subsurface layer of the OA material.

In turn, the erosion sufficiency probabilities of the ultrajet action, taking into account a highly multidimensional nature of the formation of the stress-strain state (SSS). Particularly, the probabilistic nature of defect-active pulses of elastic deformation waves can be drawn up using analogy with (1) and (2) as follows:

$$P_S = e^{-C_S \cdot x} \quad (3)$$

$$P_V = e^{-C_V \cdot x} \quad (4)$$

where $P_S(x)$ and $P_V(x)$ are the probabilities of the presence of defect-active impulses of elastic deformation waves in a sufficiently thin analyzed surface layer of the material, and in the general case of fluctuations of the SSS that can lead to critical growth of surface and subsurface defects respectively; C_S and C_V are the average "concentrations" of these defect-critical ultrajet pulses impacting the surface and subsurface layer of the OA material

Based on the informative-physical logic of the above relations, it is not difficult to notice that (1) and (2) are the necessary, and (2) and (3) are the sufficient conditions for the material particle separation due to ultrajet erosion of the surface layer of the diagnosed OA due to the critical growth of the surface and/or subsurface defect. Therefore, according to the addition theorem of probability [13], we have:

$$P_{\Sigma}(x) = P(s) \cdot P_S(x) + P(v) \cdot P_V(x) - P(s) \cdot P_S(x) \cdot P(v) \cdot P_V(x) \quad (5)$$

where $P_{\Sigma}(x)$ is the probability of erosion particle separation with a characteristic geometrical size x.

Thus, dependence (5) with consideration to (1)-(4) represents the probabilistic model of an eroded material particle formation. And within the framework of the problem being solved for the given conditions of the ultrajet action (ultrajet velocity and approach angle, as well as the active dynamic hydro contact spot S) the relation (1) takes approximately the same values.

3 Mathematical modeling results

The overall probability of erosion-conditioned separation of a particle from material surface $P_{\Sigma}(x)$, described by the formula (5), is a rather complicated nonlinear dependency. The computational results for this dependency obtained using MathCAD 15 software are presented in Fig. 2.

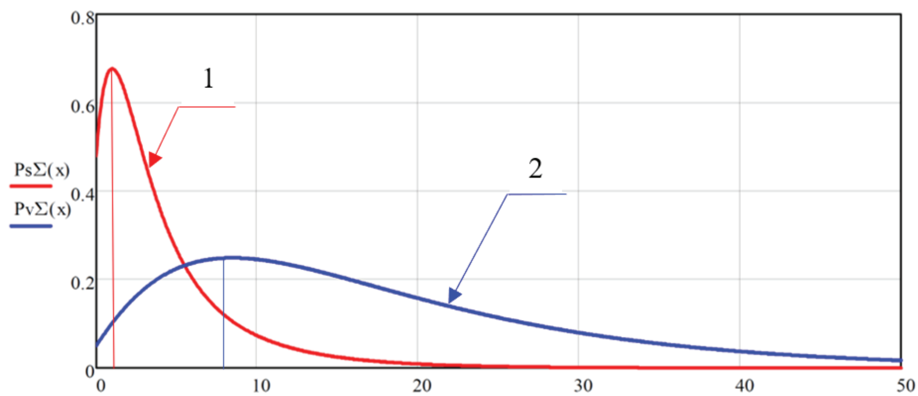

Fig. 2. Probability distribution of eroded particle sizes as a function of initial defect concentration: 1 – prevailing surface defectiveness of the material; 2 – prevailing defectiveness of the subsurface layer of the material.

The analysis of the computational data obtained has shown that a large number of small eroded particles can be expected if surface defects concentration is larger than the subsurface one ($C_S \gg C_V$) (Fig. 2, curve 1). However, in the opposite situation ($C_V \gg C_S$) much fewer particles but of significantly larger size will be eroded (Fig. 2, curve 2).

In further computations, when predicting the probability of particle separation from the material surface, it is also necessary to take into account the defect-initiating impulse effectiveness dependency on the ultrajet impact, which in its turn is determined by the ultrajet velocity (v) and the impact angle, i.e. the angle α between the ultrajet velocity vector v and the tangent to the surface at the ultrajet impact location (see Fig. 1a). Investigation of these ultrajet impact parameters influence is especially relevant for ultrajet mesodiagnostic of functional quality of complex curvilinear surfaces, typical for aviation, rocket, and space equipment [14-15].

4 Conclusions

The study proposes the probabilistic model of hydroerosion destruction of a surface layer of a material, taking into account the interrelation of necessary and sufficient conditions for creation of an informatively significant eroded particle. The influence of surface layer initial defectiveness on the eroded particles distribution pattern is established. It presents an opportunity for additional scientifically based justification of informative value of UJM as a means for quality assurance of aviation and rocket equipment.

This probabilistic approach allows taking into account random factors, which can affect the process of particle separation from the material surface. Therefore, it can be recommended when developing methods for the express quality control of materials with properties which cannot be described a priori by known mathematical dependencies.

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