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Life cycle assessment of technical systems taking into consideration degradation processes in materials of constructions

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ABSTRACT

Purpose: In the engineering analysis and transport forensic examination, there are often arise problems in establishing the causes and mechanism for the destruction of structural elements. At the moment, such problems are poorly formalized and practically do not take into account the degradation of the material and the gradient of its properties when destroyed. The purpose of this article was to build a methodology for determining the distribution of material properties at the initial time and establishing its compliance with the requirements of regulatory documentation.

Design/methodology/approach: As a technique for solving the problem, was proposed the expansion of a function in a given basis with subsequent refinement of the solution using iterative algorithmic schemes.

Findings: Using the developed approaches, it is established that in the surface layers of 12X18H10T steel (AISI 321), after technological modification under the conditions of laser doping, functional-gradient layers are formed with the material viscosity level characteristics at 0.8, which corresponds to the established norms, and their destruction occurred as a result of excessive loads.

Practical implications: With the using of the developed methods makes it possible to solve the problem of technical forensic examination to determine compliance to the requirements the properties of functional gradient materials in initial time.

Originality/value: The technique of solving inverse problems of fracture mechanics for functional gradient materials is shown for the first time.

Keywords: Life cycle, Mathematical model, Degradation of materials, Inverse problems of mechanics

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

In the design of high-loaded elements of structures that operate under unsteady conditions, it is important to take into account changes in the structure of the material in order to increase the life time of the parts and to ensure the specified safety operation parameters of the entire mechanism. The research and design follow-up of such engineering solutions requires the application of approaches that evaluate the reliability of machines taking into account the view of component material as a dynamic system that tends to change its characteristics substantially over time [1,2].

The similar problem class also appears during expert examination of railway accidents which are connected with destruction of rolling stock when the failure of the structural elements occurs at loads much below the acceptable level [3,4].

2. Presentation of the main material

2.1. Preparing relations of the mathematical model

One of the commonly accepted ways to assess life cycle of structures in their operation conditions is to use the approaches of fractures mechanics and damaged environments [4,5].

The term "fracture" has an unambiguous interpretation in most literature sources and it is understood as a defect (discontinuity of material) with a characteristic dimension of more than 10^{-3} m [5]. At the same time, the term "damage" (or "damageability") has various interpretations [5-7]. In this paper, under the term "damageability" we will understand the additive variable of scalar nature, the dynamics of which characterizes degradation or regeneration of the structure of material with dimensional parameters of defects from 10^{-8} to 10^{-4} m.

As far as the crack development and changes in the material structure of the details are interconnected processes, that take place simultaneously, the following mathematical model of mechanics is proposed:

$$\begin{cases} \Delta l(x,\tau+\Delta\tau) = K\left(l(x,\tau),\{M(x,\tau)\},\hat{\sigma}(x,\tau),T(x,\tau)\right)\cdot\Delta\tau \\ \Delta\omega(x,\tau+\Delta\tau) = f\left(\omega(x,\tau),\{M(x,\tau)\},\hat{\sigma}(x,\tau),T(x,\tau)\right)\cdot\Delta\tau \\ \{M(x,\tau)\} = \{M(\omega(x,\tau))\} \end{cases}, \quad (1)$$

where: $l(x,\tau)$ – fracture path, $\{M(x,\tau)\}$ – set of studied properties of the body, $\hat{\sigma}(x,\tau)$ – stress tensor, $T(x,\tau)$ – temperature, τ – time, $K(\ldots)$ – composite function responsible for fracture development, $f(\ldots)$ – composite function responsible for damage development.

In direct statement of a problem with known external loads and initial conditions, the value of fracture path and damage development are set in the given moment of time of the part's operation. At the same time, it is important to set (regulate) critical values of parameters $l_{кр}$ and $\omega_{кр}$ which cannot be allowed in the operation conditions.

Such problems belong to direct problems of mechanics.

In the reverse (retrospective) statement, which is typical for expert examinations, it is necessary to specify the regularities for the fracture and damage development according to known loads and the final values of given quantities.

To look for the solution to the above-mentioned problem we will apply the modified Tikhonov-Ivanov approach that is used in solving inverse problems of mechanics:

$$K^*(\ldots), f^*(\ldots): \begin{cases} \inf\limits_x \left\| l_0(x,\tau) - l_*(x,\tau) \right\| \\ \inf\limits_x \left\| \omega_0(x,\tau) - \omega_*(x,\tau) \right\| \end{cases}, \quad (2)$$

where $\|..\|$ – the norm in the respective space.

In case, when

$$K^*(\ldots) = \sum_{i=1}^{n} \alpha_i K_i(\ldots), \quad \omega^*(\ldots) = \sum_{i=1}^{m} \beta_i \omega_i(\ldots) \quad (3)$$

where: $\omega_i(\ldots)$, $K_i(\ldots)$ – known regularities in the development of damageability and fractures, the problem (2) appears as follows:

$$\{\alpha_1,\ldots,\alpha_n\},\{\beta_1,\ldots,\beta_m\}: \begin{cases} \inf\limits_x \left\| l_0(x,\tau) - l_*(x,\tau) \right\| \\ \inf\limits_x \left\| \omega_0(x,\tau) - \omega_*(x,\tau) \right\| \end{cases}. \quad (4)$$

Problems (2)-(4) may be solved both by Monte Carlo method, using genetic algorithms and by factorization in the sought basis.

2.2. Method of life cycle simulation of elements of highly-loaded structures

To illustrate the above mathematical approaches, let us consider the practical identification problem in determining conformity of the material in the initial moment of time with the requirements of regulatory documents [3].

Let us consider simulative approximation of fracture development problem in the critical structures of the rolling stock which have inhomogeneity in the distribution of properties which appears as a result of technological modification.

We will make the analysis of two-dimensional contact problem on the interaction of a rigid stamp with a fragment of an elastic half-space. In the contact interaction area, stamp vertical movements are specified, and the fragment of the material is fixed along the unloaded boundaries (Fig. 1).

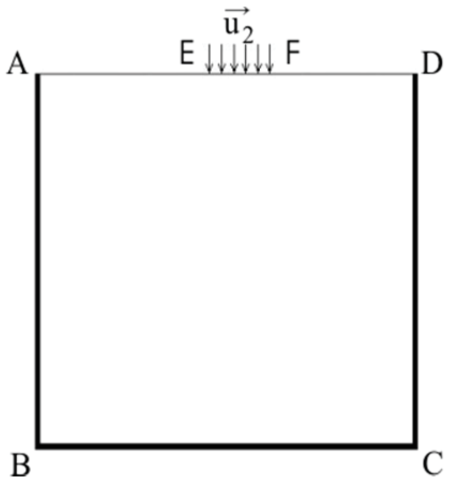

Fig. 1. Two-dimensional problem formulation for a fragment of material (AB, BC, CD – material fragment fixation, EF – area with set vertical components of displacement vector)

The finite-element method (variational formulation) was applied to solve the problem.

To solve the formulated problem, a program was developed in Maple environment. The program looks for solutions in displacements, deformations and tensions. The program was checked on test examples, which were obtained by comparing the results of numerical and analytical solutions, presented in classical monographs on contact problems [8].

It is accepted that mechanical properties of materials by depth are changed according to the law:

$$f(z) = f_0 + f_1 e^{-h \cdot z}, \quad (5)$$

where:
f_0, f_1, h – constants, characterizing the properties of near-surface areas with known technological (operation) influences, and z – depth.

When establishing the paths of fracture propagation in damage mechanics, the methods which may be divided into two groups are applied. These are differential (step-be-step) methods, which are based on local damage criteria, and integral (global) methods, which are based on criteria determined through integrals along the sought lines.

In this paper the integral damage criterion was applied, according to which the fracture propagation path will pass through the areas where the tensions satisfy the correspondence of Pysarenko-Lebedev criteria [9]:

$$\chi\sigma_i + (1-\chi)\sigma_1 = [R], \quad (6)$$

where:
[R] – threshold strain level, σ_i – main strains, χ – parameter characterizing the degree of participation of the sheer deformation in the macro-damage and it is determined as: χ= *Rp/Rcm,* where *Rcm*, *Rp* – strength boundary for compression and extension respectively ($0 \le \chi \le 1$). For loose materials $\chi = 0$, and for viscous materials $\chi = 1$.

Let us determine the influence of parameter χ (toughness of material) on fracture propagation path. We find χ according to the formula:

$$\chi: \left\| l(x,y) - l_p(x,y,\chi) \right\| \to 0, \quad (7)$$

where:
$l_p(x,y,\chi)$ – predicted fracture path, $l(x,y)$ – measured fracture path.

To find the solution of χ parameter, iteration method was used as presented in Figure 2.

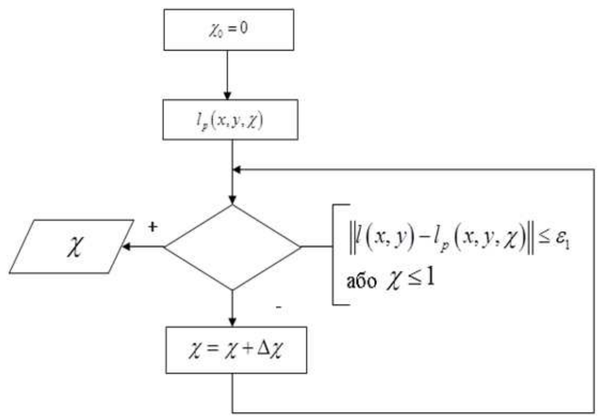

Fig. 2. Iteration algorithm to find parameter χ

If parameter χ, that satisfies the condition $\chi: \left\| l(x,y) - l_p(x,y,\chi) \right\| \le \varepsilon_1$, does not exist, it is necessary to use another fracture criterion, that would describe this weakening mechanism more exactly.

For a numerical example, a change in the mechanical properties in the near-surface layers of a 12H18N10T steel material after laser doping was used. The loading rate is set at $|\vec{p}| = 5$ MPa. As a result, with the accuracy ε=0.1 we accept a hypothesis of parameter value χ=0.8.

When comparing the results obtained according to the method developed in this work with the results of the work [9], it is possible to determine that the condition of material in the initial moment of time satisfied the established norms and the failure of the component was caused by excessive loads.

3. Conclusions

1. The paper suggests the methods of life cycle simulation and research the failure of the parts that are operated under conditions of intensive external loads.
2. The possibility of the developed approaches, which may be used for determining conformity of mechanical parameters of functionally graded surface layers to specified parameters during their operation was demonstrated.
3. Further development of the formulated approach is expected in the direction of further expansion of modelling views (4), (5) and improvement of problem search algorithms of type (6).

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