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Analysis of friction interaction and optimisation of detail surface hardening technologies using non-local mathematical models

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ABSTRACT

Purpose: The aim of the work is to build physically sound engineering and design schemes that take into account the behaviour of polycrystalline metal systems under intense loads and allow optimization of surface treatment technologies to increase the operational reliability parameters of products.

Design/methodology/approach: Using the approaches of thermodynamics, a methodological scheme is proposed, on the basis of which it is possible to optimize surface engineering technologies to increase the contact durability of details.

Findings: It was found that the maximum increase in the durability of steel 40X13 (AISI 420) is achieved with thermocyclic ion nitriding in a cycle of ± 50°C, and the minimum with isothermal nitriding.

Research limitations/implications: In this paper, the optimization of technological solutions to increase the contact durability of structural elements operating under prevailing power loads is given.

Practical implications: Using the proposed mathematical relationships, optimal technological regimes of ion-plasma nitriding were established for various operating conditions, under which the maximum durability and wear resistance of 40X13 (AISI 420) steel are ensured.

Originality/value: The paper proposes an approach to the formation of functionally gradient surface layers of steel with specified operational parameters when choosing optimal nitriding technology modes based on nonlocal mathematical models.

Keywords: Friction, Surface engineering, Non-local mathematical model, Optimisation

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ANALYSIS AND MODELLING

1. Introduction

The development of scientific bases, methods of evaluation and forecasting of parameters of machine details and mechanisms performance under intensive contact loads is one of the priority problems of modern mechanical engineering [1]. Analytical review of the research results devoted to the issues of mechanical systems calculation under friction load conditions is given in the works [2]. The analysis of these works allows concluding that approaches to modelling of metal systems under the friction and wear conditions are mainly based on linear mechanical models.

At the same time, a wide introduction of modern technologies of detail surface hardening by directed formation of locally non-uniform structures permits broad changing of product operational parameters. Management of these technologies requires the development of appropriate mechanics models that incorporate processes associated with energy dissipation under operating loads, especially within conditions of locally concentrated deformation [3].

At present, it is generally recognized that during deformation the energy dissipation in metals occurs due to internal transformations in their structure [4]. Physical mechanisms of dissipation can vary, but they contribute to the reduction of deformation energy, the level of body stresses and, in some instances, allow extending the product life through the formation of spatial structures in the material that meet component conditions. These mechanisms of energy dissipation are specifically manifested in friction interaction conditions, when the transfer of loads bears a high-intensity local character.

The calculation of operational parameters of contact bodies is currently carried out according to "classical" models of mechanics, which do not take into account energy dissipation. Such models, except for convenience of their numerical use as well as experimental substantiation sufficient for engineering practice, also have several disadvantages, i.e. for some canonical contact bodies, in particular a rectangular stamp, the calculated level of stresses in edge zones will equal to infinity [5].

In connection with this, there exists a need to improve current model computational schemes under the conditions of friction contact and modification of mechanics models in order to take into account mechanisms of energy dissipation in a material at the model level.

2. Task formulation. Building model relationships

At formulating equations of a non-local mathematical model, let us accept postulates of the thermodynamics of open systems regarding the possibility of representing the deformation energy as a sum of reversible and non-reversible components [6].

Let us relate a reverse component of energy to elastic deformations with respect to the Hook's law, and a non-reversible component to rotary and translational effects in the material structure [4]. It should be noted that these effects are always present in metals during their deformation and are manifested as a redistribution of dislocations in space or movement of micro-damages. The above phenomena become most prominent in near-surface detail zones when a frictional contact of bodies occurs. At the level of mathematical relations, the first component of the generalised energy functional (a reversible component of the deformation energy) will depend on a symmetric component of the deformation tensor, while the second component (a non-reversible component of the deformation energy) will depend on a displacement vector and an anti-symmetric component of a deformation tensor.

One of the local equilibrium thermodynamics postulates is an a priori assumption regarding the linear dependence of energy functional growth from its components [6, 8]. In this connection, taking into account the dependence of intensity of translational and rotational processes from the current level of a body damage, we receive the following equilibrium equation for elastic media unexclusive of the possibility of energy dissipation during deformation:

$$\begin{aligned}&\vec{\nabla}_0\cdot\Big(\Big(K(x)-\frac{2}{3}G(x)\Big)\big(\vec{\nabla}_0\cdot\vec{u}\big)\cdot\hat{I}+2G(x)\big(\vec{\nabla}_0\otimes\vec{u}\big)^s+\\&+2B(x,\omega)\big(\vec{\nabla}_0\otimes\vec{u}\big)^a\Big)-2A(x,\omega)\vec{u}=0\end{aligned}, \qquad (1)$$

where: a scalar product of vectors, $\otimes$ – a tensor product, $\vec{\nabla}_0 = \frac{\partial}{\partial \vec{r}}$ – the Hamiltonian operator, $\vec{u}$ – a displacement vector, $K(x)$ – a bulk compression modulus, $G(x)$ – a shear modulus, $(\vec{\nabla}_0 \otimes \vec{u})^s$ – a symmetric deformation tensor, $(\vec{\nabla}_0 \otimes \vec{u})^a$ – an anti-symmetric deformation tensor, $\hat{I}$ – an identity tensor, $A(x,\omega)$, $B(x,\omega)$ – characteristics of relevant translational and rotational relaxation processes, ω – the level of damage present in a body.

If the influence of energy dissipation is not taken into account, that is to say, if we take $A(x,\omega)=0$, $B(x,\omega)=0$, then we get a classical equation of the elasticity theory in displacements for structurally heterogeneous isotropic material, and at $K(x)=const$, $G(x)=const$ there is a "classical" equation of the elasticity theory:

$$G\Delta\vec{u} + \left(K + \frac{1}{3}G\right)\vec{\nabla}_0\left(\vec{\nabla}_0 \cdot \vec{u}\right) = 0. \quad (2)$$

As can be seen from the above proposed dependencies, a resulting generalized equation (1) in simpler cases takes into account classical relations of the elastic systems mechanics (2).

3. Application of the results

Let us use the built-up relations for solving of applied problems concerning the analysis of local friction interaction of bodies and Optimisation of technologies of hardening of detail surface layers by ion nitriding.

3.1. Analysis of the built-up model for bodies under local contact loads

One of the features of rubbing interaction of bodies is the local transmission of loads. It is caused both by a complex profile of the contacting bodies surface, and transfer of loads under friction conditions.

In mechanics, multiple and single rubbing contacts are considered. Besides, the influence of an aggregate multiple contact (adjacent contact zones) on the value of stress-strain state within the region of a single (isolated) zone of interaction is insignificant and makes on average 5%. In this connection for calculation and analysis of behaviour of bodies under friction conditions the problems regarding local friction load are used [5].

In this paper we consider a two-dimensional classical contact problem regarding the local friction load of an elastic half-plane by a rigid rectangular die affecting an isotropic elastic half-plane (Fig. 1) [5,7].

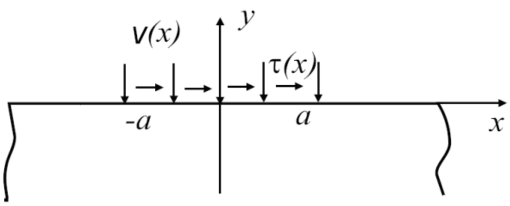

Fig. 1. Elastic half-plane force load: a – contact patch radius (body interaction region), $\tau(x)$ – tangential stresses, $v(x)$ – vertical movement

In the orthonormal Cartesian system of coordinates let us consider the following "classical" problem regarding the friction load of a body: in the region of $y=0$, $|x| \le a$ we specify vertical loads; the relationship between tangential and regulatory components of a load vector is presented by the Coulomb's law $\sigma_2(x) = k \cdot \sigma_1(x)$, where $k \in (0;1)$, $\sigma_1(x)$ is a load vector vertical component, $\sigma_2(x)$ is a load vector tangential component (Fig. 1) [5].

The problem will be solved by means of Fourier series transformation [10]. Let us set variable $\vec{u}_2(x,0)$ to $\vec{u}_2(x,0) = \{0.001,\ |x| \le 1; 0,\ x > 1\}$. As a material we choose steel 40X13 (international equivalent – AISI 420) since it is used as a hardware material of details which in the process of mechanical engineering are exposed to technological modification (surface treatment) and work under the conditions of frictional interaction. Let us assume that $A(x,\omega) = \alpha \cdot E$, $B(x,\omega) = \beta \cdot E$, where coefficients are $\alpha = 0.1$, $\beta = 0.2$. These relations show that relaxational (translational) properties in the material are closely related with the parameters of its mechanical properties.

The problem was solved using Maple software [11]. As a result, the following values of von Mises equivalent stresses were received and they are shown in Figure 2.

As can be seen, the material behaviour on the detail surface significantly changes due to energy dissipation under loads. The level of stresses generated in contact load regions becomes significantly reduced, and the nature of deformations becomes different. The friction coefficient value k also influences the behaviour of a body in the contact region as a result of redistributing of the stress from the region middle part to its edge.

This allows us to make an important practical conclusion, i.e. to reduce the level of stresses in a body at given loads, it is necessary to form dissipative structural components in the material (especially in near-surface regions), which allow for energy dissipation through internal transformations [4]. This can partly be achieved by modifying surface layers using different technological methods.

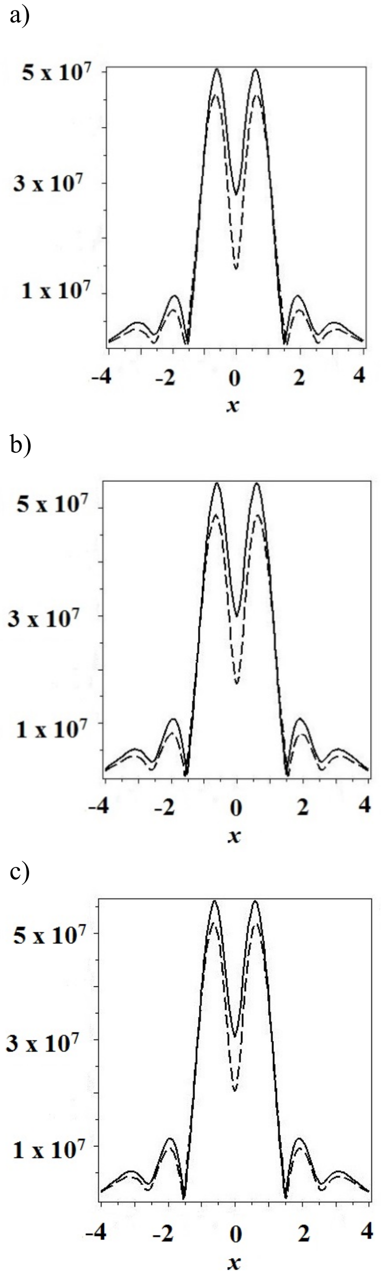

Fig. 2. Values of von Mises equivalent stresses on 40X13 (AISI 420) steel contact interaction surface at the presence (dashed line) and absence (solid line) of energy dissipated in a body and at the friction coefficient k: a) $k = 0$; b) $k = 0.2$; c) $k = 0.4$

3.2. stablishment of nitriding technologies optimal modes based on the built-up model

We use the above problem statement regarding frictional load of non-local media for Optimisation of one of the most widespread technologies of surface hardening, namely thermal cyclic ion-plasma nitriding.

The advantages of this technology is a significant increase in contact strength and durability of surface layers while maintaining the parameters of their micro-geometry. Besides, if this type of strengthening is applied, the necessity in finishing aiming at detail profile restoration becomes eliminated [3,12].

Let us study the contact strength of samples made of 40X13 (AISI 420) steel, which were subjected to ion-plasma thermocyclic nitriding under the following modes: isothermal nitriding, ± 50°C cyclic nitriding, ± 100°C cyclic nitriding.

Modelling of the behaviour of bodies under friction load conditions alongside with the numerical evaluation of their operating parameters requires setting of parameters of mechanical characteristics of the material in respect of its depth. The results of determining steel microhardness after application of different modes of nitriding are shown in Figure 3.

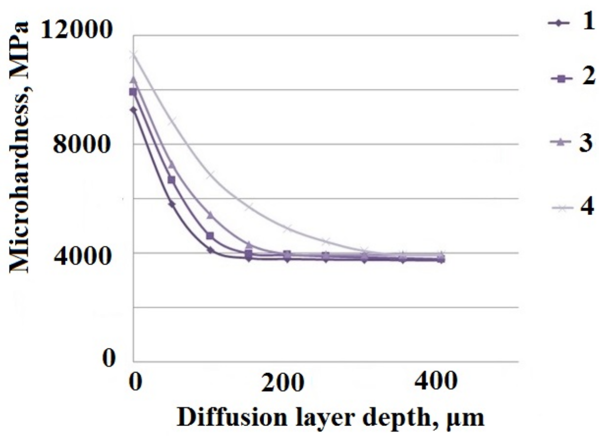

Fig. 3. Experimental data for measuring microhardness of surface layers in various modes of ion-plasma nitriding: 1 – isothermal nitriding, 2 – ±25°C cyclic nitriding, 3 – ±100°C cyclic nitriding, 4 – ±50°C cyclic nitriding

At approximation of received results, it is a priori assumed that functional dependences of mechanical characteristics of a material in the studied region belong to L^2 function class [10]. The type of received dependence diagrams (Fig. 3) allows us to consider that the interpolation procedure is better performed using exponential function matching:

$$F(x) = C_0 + C_1 e^{-Dx}, \quad (3)$$

where C_0, C_1, D – numerical constants, $F(x)$ – microhardness diffusion in respect of material depth, x – distance from the surface.

The method of least squares was used to establish the functional relationship [10].

As a result, the following analytical dependencies of microhardness changes in respect of material depth were received:

for isothermal nitriding:

$$F_1(x) = (3726.508 + 5540.729 \cdot e^{-0.02185153668 \cdot x}) \cdot 10^6, \quad (4)$$

for ±25°C cyclic nitriding:

$$F_2(x) = (3775.541 + 6129.125 \cdot e^{-0.01746421493 \cdot x}) \cdot 10^6, \quad (5)$$

for ±50°C cyclic nitriding:

$$F_3(x) = (3922.64 + 7354.95 \cdot e^{-0.009584234361 \cdot x}) \cdot 10^6, \quad (6)$$

for ±100°C cyclic nitriding:

$$F_4(x) = (3922.64 + 6472.95 \cdot e^{-0.009584234361 \cdot x}) \cdot 10^6. \quad (7)$$

Since the subject of our study were 40X13 (AISI 420) steel samples used as material for manufacture of gas turbine engine blades, let us assume that these samples will operate under the conditions of prevailing gas-abrasive wear in parallel with possible cavitation wear [7].

Therefore, let us consider that contacting under these conditions occurs not over the entire surface, but only in the region of contact patches, the diameter of which on average is equal to 30 µm, and the stress within a contact patch approaches to the yield limit.

Let us assume that the load pure within a contact patch region is of parabolic structure (Fig. 4), which is characteristic at the introduction of solid spherical particles in a body surface as well.

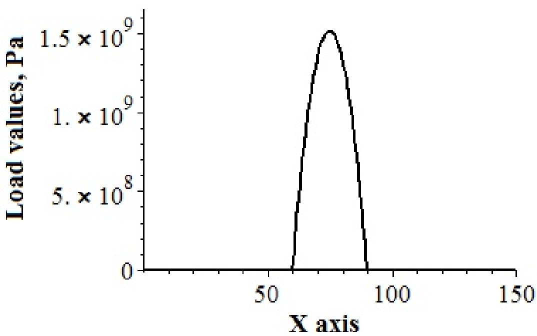

Fig. 4. Local load function diagram

This load (Fig. 4) causes the occurrence of stress areas, shown in Fig. 5, in study samples.

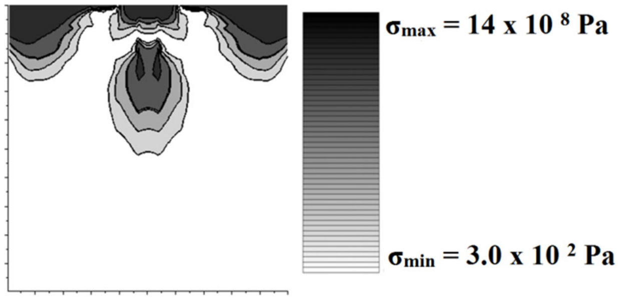

Fig. 5. Stress distribution in a sample upon isothermal ion-plasma nitriding

Since the stress state does not unambiguously determine the contact strength of friction node surface layers, we analysed changes in the size of zones, generated as a result of the load action, at various load factors (Fig. 6) in accordance with the formula:

$$z = \frac{\sigma_0}{\sigma_*}, \quad (8)$$

where σ_0 is the representation of stress-strain state by means of equivalent stresses using Pysarenko-Lebedev criterion ($\sigma_0 = \chi\sigma_i + (1-\chi)\sigma_1$, σ_i – the stress intensity, σ_1 – the first main stress, χ – the material plasticity parameter, $\chi = \frac{\sigma_p}{\sigma_c}$, σ_p is the ultimate tensile stress, σ_c is the ultimate compressive strength (for plastic materials $\chi = 1$, for brittle materials $\chi = 0$), σ_* – material strength properties.

The presented results (Fig. 6) show that samples treated in the process of ion-plasma thermocyclic nitriding will behave better under friction conditions as compared to those treated in the process of isothermal nitriding. The contact strength is also significantly influenced by the modes of surface hardening depending on the operating conditions. Thus, at frictional contact loads $p_{max} \leq 3.02 \cdot 10^9$ Pa it is reasonable to apply isothermal nitriding, at loads $3.02 \cdot 10^9 \leq p_{max} \leq 3.23 \cdot 10^9$ Pa it is reasonable to apply ±25°C isothermal cyclic nitriding, at loads $3.23 \cdot 10^9 \leq p_{max} \leq 3.38 \cdot 10^9$ Pa – ±100°C cyclic nitriding, and at loads $3.38 \cdot 10^9 \leq p_{max} \leq 3.67 \cdot 10^9$ Pa – ±50°C cyclic nitriding nitriding.

It should be noted that the choice of modes of technological modification of surfaces by ion isothermal and thermocyclic nitriding proposed in the work corresponds to modern trends regarding the creation of materials with a set functionally graded structure. Such materials, called “smart materials” [12], are capable to dissipate energy at loads and eliminate structure defects due to self-organizational processes.

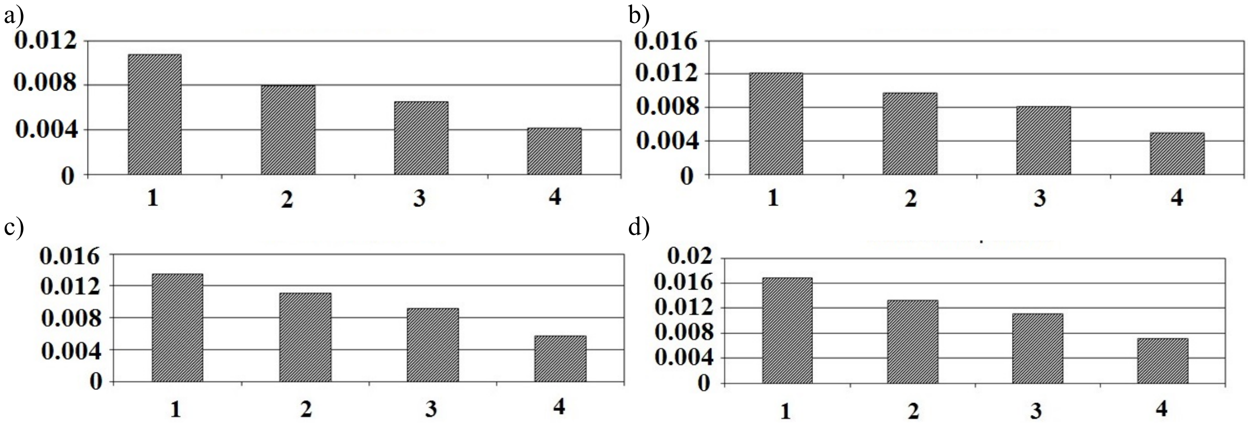

Fig. 6. Changes in the specific size of zones with a contact strength factor of 0.8 for surfaces with various parameters of functionally graded coating under: a) $p_{max} = 3.02 \cdot 10^9$ Pa, b) $p_{max} = 3.23 \cdot 10^9$ Pa, c) $p_{max} = 3.38 \cdot 10^9$Pa, d) $p_{max} = 3.67 \cdot 10^9$Pa, here 1 – sample after isothermal ion-plasma nitriding, 2 – sample upon ±25°C cyclic nitriding, 3 – sample upon ±100°C cyclic nitriding, 4 – sample upon ±50°C cyclic nitriding

4. Conclusions

1. The current state of the problem of frictional interaction of bodies and management of surface hardening technologies has been analysed in the paper.
2. To estimate non-local transformation changes occurring in the material structure at intensive loads a mathematical model that takes into account rotation dissipative effects in a continuum description of the medium has been proposed.
3. The built-up relations are used at solving of applied problems concerning the analysis of local frictional interaction of bodies and Optimisation of technological modes of detail surface layer hardening in the process of ionic nitriding.

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