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Interfacial fracture of thin elastic layers due to cyclic load

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Abstract

Fracture of thin surface layers, which are harder or softer than the substrate material, is considered for the case of cyclic sliding contact. The study is based on modeling of multiple and single contact of two-layered elastic half-space, identification of elastic properties of the surface layers from indentation results, theoretical and experimental study of relatively hard coatings delamination due to contact fatigue, which arises at the level of asperities. The parameters of damage accumulation law at the coating-substrate interface for two component oxide coating are estimated. The properties of relatively soft coatings, which arises during friction of aluminium alloys because of soft faze extrusion are obtained from indentation data.

Keywords: Surface layers, contact problem, contact fatigue, indentation, friction tests

1. Introduction

The paper is devoted to fracture of thin surface layers in cycled friction contact. Mechanical properties of the layers differ from the properties of the substrate. Such layers can be deposited to improve friction or wear resistance, or can appear during the friction process for the case of materials with the properties of self-lubrication.

Two types of non-uniform bodies are under consideration. Coatings deposition is one of the widespread methods to improve tribological properties of friction joints (Holmberg and Matthews (2009)). Thin surface layers with specific properties can be also obtained during the friction contact because of self-lubrication effect, such materials are used when standard lubrication is impossible (Bushe et al. (2003)).

Here we consider thin (up to 400nm) nano-structural coatings based on multi-component oxides composed in different proportions. The materials are characterized by high resistance to heating and the coatings have good

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adhesion to the substrate (Sakharov et al. (2013)). It was obtained by Torskaya et al. (2013) that the main mechanism of the coatings fracture in friction contact depends on loads and velocity conditions, and the value of friction coefficient. In this study the contact fatigue at the coating-substrate interface is analyzed.

Another type of material under consideration is aluminium alloys with small amount of other elements (with Al, Si, Cu, Sn, Pb in different proportions). The tribological properties of the alloys were studied by Kurbatkin et al. (2014). Sn and Pb are the soft components, which are extruded from the base materials during friction loading because of deformation and temperature effects. It leads to the formation of specific surface layer, which mechanical properties and the possibility of fracture control during friction are also studied here.

2. Contact problem formulation and the method of solution

Contact of a periodic system of spherical indenters of radius R on the boundary of a layered elastic half-space (Fig. 1) is considered. The indenters are located at the nodes of a hexagonal lattice with period l. The system is loaded by the period-averaged nominal pressure p_n. The layered elastic half-space consists of an elastic layer of thickness h and an elastic half-space; elastic properties of the layer and the half-space are characterized by the elasticity moduli E_i and the Poisson ratios ν_i ($i = 1, 2$ for the layer and for the half-space, respectively).

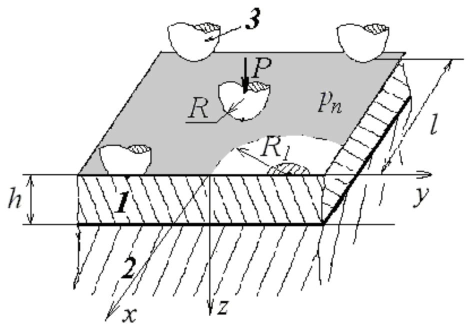

Fig. 1. Scheme of the periodic contact

For a system of axially symmetrical indenters located at the nodes of a hexagonal lattice (3, Fig. 1), the relation between the load P acting on each indenter and the nominal pressure p_n is the following:

$$P = (\sqrt{3}/2)\, p_n\, l^2 \tag{1}$$

where l is the lattice period.

The conditions at the interface ($z = h$) between layer and substrate are determined by the relations

$$\sigma_z^{(1)} = \sigma_z^{(2)}, \quad \tau_{xz}^{(1)} = \tau_{xz}^{(2)}, \quad \tau_{yz}^{(1)} = \tau_{yz}^{(2)}, \quad w^{(1)} = w^{(2)} \tag{2}$$

Here $\sigma_z^{(i)}, \tau_{xz}^{(i)}, \tau_{yz}^{(i)}$ are the normal and shear stresses, and $w^{(i)}, v_x^{(i)}, v_y^{(i)}$ are normal and tangential displacements of the elastic layer ($i = 1$) and the elastic substrate ($i = 2$).

The following boundary conditions on the upper layer surface ($z = 0$) written in polar coordinates (r, θ) related to a fixed indenter, are considered:

$$\begin{aligned} & w(r) = f(r) + \delta, \quad 0 \le r \le a \\ & \sigma_z^{(1)} = 0, \quad a < r < R_1 \\ & \sigma_z^{(1)} = -p_n, \quad R_1 \le r < \infty \\ & \tau_{rz}^{(1)} = \tau_{\theta z}^{(1)} = 0, \quad 0 \le r < \infty \end{aligned} \tag{3}$$

Here $f(r)$ is the indenter shape, δ is the indenter displacement along the axis (Oz), a is the radius of a contact zone ω_i. The boundary conditions (3) are obtained using the localization principle formulated and proved by Goryacheva (1998) for the case of penetration of a periodic system of indenters into the elastic half-space. The accuracy of the solution based on the problem formulation with boundary conditions (3) in comparison with one obtained from the exact problem formulation for the periodic system of indenters on the elastic half-space is also estimated by Goryacheva (1998). To obtain the pressure distribution under a fixed indenter inside a contact region $r \le a$, the action of the other indenters is replaced by the action of the nominal pressure p_n distributed outside the circle with radius R_1 (Fig. 1). The radius R_1 is determined from the equilibrium equation and (1) as

$$R_1 = (P / (\ p_n))^{1/2} = (\sqrt{3} / (2\pi\ ))^{1/2} l \ \cong \ 0.525\ l \tag{4}$$

The equilibrium equation has the form

$$P = \int_0^a \int_0^{2\pi} p_s(r) r \, \mathrm{d}r \, \mathrm{d}\varphi \tag{5}$$

where $r = \sqrt{(x - x_c)^2 + (y - y_c)^2}$ (x_c and y_c are the coordinates of the center of the fixed indenter), $p_s(r)$ is the contact pressure distributed at each contact spot ω_i ($p_s(r) = -\sigma_z(r),\ r \in \omega_i$).

The solution of the axisymmetrical contact problem for the layered elastic half-space with boundary conditions (2) and (3) is obtained by the method presented by Goryacheva and Torskaya (2003). It consists of two stages. The first stage is to find the shape $g(r)$ of the deformed surface of the unloaded circular region $0 \le r \le R_1$ caused by the pressure p_n applied outside this region ($R_1 \le r < +\infty$); the following boundary conditions at the upper layer surface ($z = 0$) are considered

$$\begin{aligned} & \sigma_z^{(1)} = 0, \quad 0 < r < R_1 \\ & \sigma_z^{(1)} = -p_n, \quad R_1 \le r < \infty \\ & \tau_{rz}^{(1)} = \tau_{\theta z}^{(1)} = 0, \quad 0 \le r < \infty \end{aligned} \tag{6}$$

The problem is solved by using the Hankel integral transforms. The main ideas of the method were first presented by Nikishin and Shapiro (1970).

At the second stage, the function $g(r)$ is used to formulate the boundary conditions at the upper surface ($z = 0$) of the elastic layer. To solve the contact problem, we divide the contact zone into K rings of equal thickness and determine the contact pressure as a piecewise function. The problem is reduced to the following system of equations to determine the contact pressure:

$$
\begin{aligned}
& p_1 k_1^{(i)} + p_2 k_2^{(i)} + \ldots + p_K k_K^{(i)} = f'(r_i) \\
& i = 1, 2, \ldots, K-1 \\
& \pi \sum_{i=1}^{K} p_i (r_i^2 - r_{i-1}^2) = P \\
& f'(r) = (f(r) - f(a)) - (g(r) - g(a))
\end{aligned} \tag{7}
$$

To find the unknown radius of the contact zone, the condition of zero pressure on the boundary of the contact zone is used and the iteration method is applied. To calculate internal stresses especially between the contact spots we need to use superposition

For the case of $p_n \equiv 0$ we have the contact problem for a single indenter.

3. Determination of elastic properties of coatings and thin surface layers from indentation data

The fracture of coatings and thin surface layers in contact interaction depends on contact stresses. We need to know elastic properties of contact bodies to calculate the stresses. Usually the elastic properties are taken from the parameters of bulk materials or from indentation tests with calculation of elasticity modulus using Hertz theory. But elastic properties of the thin layers may differ from the properties of bulk material; for indentation tests it is impossible to ignore the influence of substrate on the value of penetration.

Method, which bases on the contact problem solution for a single indenter, makes it possible to obtain elasticity modulus from the load-penetration dependence for a fixed point of coated surface. The method is based on contact problem solution for a ball and two-layered elastic foundation. The load-penetration dependence is obtained for a range of elasticity modulus value. The set of indentation results makes it possible to obtain the only points in the range. The method has been verified for the case of hard coatings deposited on relatively soft substrates which have been tested by micro indentation (Torskaya et al. (2013)).

Results of indentation of the coatings from Al and Zr oxides in proportion 6:1 deposited on glass are presented in Fig.2. The coating thickness is 140nm. The results were obtained by NanoTest 900; a conical diamond indenter with the tip curvature 10μm was used to provide elastic indentation with loading and unloading curves close to each other. It means that no plastic deformation or fracture takes place at the surface. For the case elastic contact problem solution can be used to identify the coating elastic properties; the substrate Young modulus is 110GPa. Ten experimental curves were obtained for the sample. The averaging procedure was used to obtain resulting experimental curve 1. It is in good correlation with calculated indentation curve for Young modulus of the coating equal to 146 GPa. This modulus will be used later for calculation of stresses in multiple contact problem.

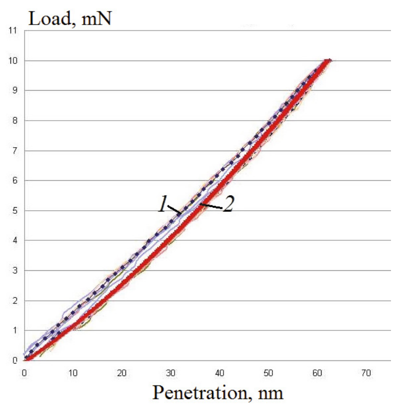

Fig. 2. Experimental indentation (curve 1) and results of calculations (curve 2) for hard coating from Al and Zr oxides

A specific feature of aluminum alloys after friction tests are unknown friction film thickness of the secondary structures and depleted surface layer, as well as mechanical characteristics of this new-formed surface layers. Thus, it is necessary to solve the inverse problem of identifying these values. It is possible to find the elastic properties and the thickness of the layer as a result of the indentation, the algorithm is presented by Torskaya et al. (2008).

. The modeling of the self-lubrication due to soft components extrusion (Bushe et al. (2003)) shows that the depleted surface layer has uniform mechanical properties from the surface to the boundary between the layer and the base material. It is a reason to use the model of two-layered foundation for identification of the properties.

For example let's consider the indentation results for the alloy with Al, Si, Cu, Sn, Pb (4% Cu, 5% Si, 6% Sn and 2% Pb). Scretch and tribological tests have confirmed the possibility of using this alloy instead of bronze in determined load and velocity conditions (Sachek et al. (2015)). Friction tests were performed according to the scheme of the reciprocating motion in the contact with steel counter body. Test parameters are the following: the amplitude of 2.5mm, the frequency of 10Hz, load 25N, test time - 30 minutes. The indentation experiments were made for initial sample and then, the same sample after the tribological tests. Nano-mechanical tester NanoScan (Useinov A.S. and Useinov S.S. (2012)) was used with an alumina ball (600GPa Young modulus, Poisson ratio 0.18, diameter 1.5mm) as a counter body. The loads up to 0.25N were used for indentation. In each case, a series of experiments were performed, the averaged results are presented in Fig. 3 (curves 1).

For the initial sample the elastic properties of the surface layer are similar to the volume properties. The calculated curve 2 in Fig.3,a was obtained for 65GPa elasticity modulus, Poisson's ratio for alloys in all cases was assumed to be 0.3. The same curve is marked as curve 3 in Fig. 3,b and used to compare the results before and after friction. It is possible to conclude that there is a surface layer with greater compliance than the base material. Estimated curve 2 in Fig. 3b was obtained for the following parameters: the thickness of the surface layer 1.5mkm, 32GPa elasticity modulus, the modulus of elasticity of the base material - 65GPa. Since we have no film of the secondary structures on the surface after the test, the result should be explained by the appearance of micro pores after separation of the soft phase during friction.

Thus the indentation results help to describe the fracture mechanism for materials with self-lubrication properties in friction contact. The new-formed depleted surface layer has low wear resistance, its wear leads to the extrusion of soft alloy components from the base material under the depleted layer, the layer thickness increase. The stabilization of the layer thickness leads to the constant friction coefficient and wear rate in fixed load and velocity conditions. It also can be controlled by indentation in different times of friction process.

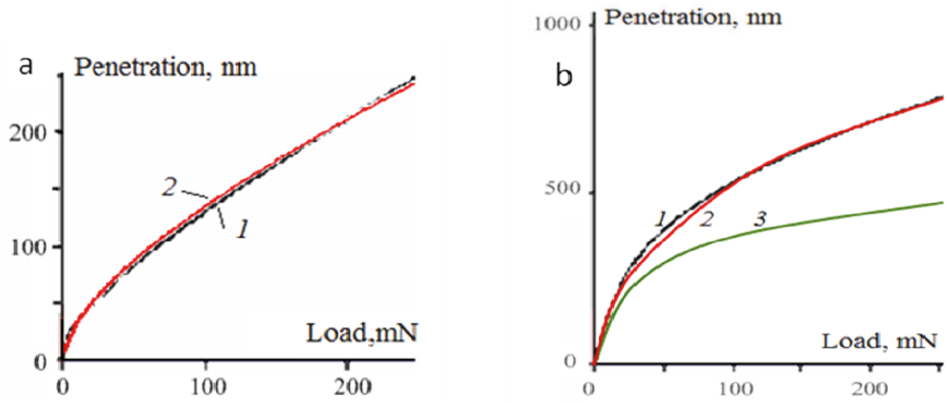

Fig. 3. Experimental indentation (curves 1) and results of calculations (curves 2,3) for aluminium alloy before (a) and after (b) tribological tests

4. Model of the contact fatigue at the layer-substrate interface

The previous studies (Kravchuk et al. (2015)) have shown that the friction without lubrication caused brittle fracture and detachment of coatings or fast wear; the mechanism depends on the value of the applied load and the friction coefficient. Sliding contact with a small amount of lubricant, which provides a small coefficient of friction, leads to the coating delamination, which occurs after a multicycle loading. Taking into account the thickness of the coating the load-unload cycles for the coating-substrate interface occurs at the micro level by contact of asperities, which can be simulated by the system of indenters.

To model the contact fatigue at the interface, we use a macroscopic approach, developed by Goryacheva and Chekina (1990, 1999). This approach was used to analyze fracture kinetics for coating material. Here we consider only the interface, because it fracture resistance is differ from the same properties of coating and substrate materials (coating delamination is one of the main reasons of the system failure). The macroscopic approach involves the construction of the positive function $Q(M,t)$ non-decreasing in time; the function characterizes the material damage at the point $M(x, y)$ of the interface and depends on the stress amplitude values at this point. To study damage accumulation, the model of the damage linear summation is used (the damage increment at each moment does not depend on the value of the already accumulated damage). The fracture occurs at the time instant t^* at which this function reaches a threshold level at some point.

There are various physical approaches to the damage modeling, in which the rate of damage accumulation $\partial Q(x, y, t)/\partial t$ is considered as a function of stress at the given point, the temperature, and other parameters depending on the fracture mechanism, the type of material, and some other factors. For the present study, we assume that the relation between the fatigue accumulation rate $\partial Q(x,y,t)/\partial t$ and the amplitude value $\Delta\tau_1$ of the principal shear stress at the point has the following form

$$q(x,y,t) = \frac{\partial Q(x,y,t)}{\partial t} = c\left(\Delta\tau_1(x,y,t)\right)^m \tag{8}$$

where c and m are experimentally determined constants and $\Delta\tau_1(x,y,t)$ is the amplitude value of the principal shear stress at the point (x, y) of the interface for one period of sliding loading.

The problem is periodic, that's why the damage function is independent of the coordinate x at the cross-section $y=const,$ and depends only on the time t (the time can be evaluated by the number of cycles N). We consider the cross-section y=0 which corresponds to the maximum value of the principal shear stress amplitude. The damage $Q(N)$, which is accumulated at the interface during N cycles, is calculated from the relation

$$Q(N) = \int_0^N q_n(n)dn + Q_0 \tag{9}$$

where Q_0 is the distribution of the initial damage in the material and $q_n(n)$ is the rate of the damage accumulation independent of the coordinates x, y.

The fracture occurs as the damage reaches the critical value. In a normalized system this condition is

$$Q(N^*) = 1 \tag{10}$$

where N^* is the number of cycles before the fracture initiation.

Calculation of the stress distribution at the interface makes it possible to find the maximum amplitude values of the principal shear stresses along the axis (Ox), which coincides with the sliding direction. The function $\Delta\tilde{\tau}_1(n)$ characterizes the maximum amplitude values of the principal shear stress.

To calculate the function of damage $Q(N)$ we use the following relationship:

$$Q(N) = \int_0^N c(\Delta \tilde{\tau}_1(n))^m \, dn + Q_0 \tag{11}$$

The damage function $Q(N)$ is calculated by summation. Under the assumption of zero initial damage Q_0, the number of cycles N^* before the first fracture is calculated from the relation following from (10) and (11):

$$N^* c(\Delta \tilde{\tau}_1)^m = 1 \tag{12}$$

The values of N^* can be obtained experimentally for different loads, and for the loads the value of $\Delta \tilde{\tau}_1$ also can be calculated. From the data the values of constants c and m should be estimated; the estimation accuracy depends on the number of different loads and the accuracy of N^* determination.

5. The experimental study of coatings detachment and calculation results

To study the cyclic loading of coatings at micro scale pin on disk friction contact (reciprocated sliding) was used with specially prepared rough counter body (Fig.4,a). The coated samples were used as pin with radius 3mm. It was obtained analytically by Goryacheva (2008) that such type of contact in the presence of roughness characterized by almost constant pressure distribution. For the case the model of multiple contact described above can be used for calculation of stresses at micro level. The counter body was prepared using sand paper to obtain roughness, which can be modeled by a periodic structure. Average roughness density is 112мм$^{-1}$, the average radius of asperities is 9µm. The data were used to determine the parameters of model system of indenters. The sliding amplitude was 2.5mm with frequency 10Hz. First the preliminary tests with different coating compositions were performed with similar load 4N. The best resistance of delamination was obtained for the coatings from Al and Zr oxides in proportion 6:1. It was chosen for the following study. For any case the friction coefficient was less than 0.1 (generally essentially smaller). That's why the model of frictionless contact was used to simplify calculations.

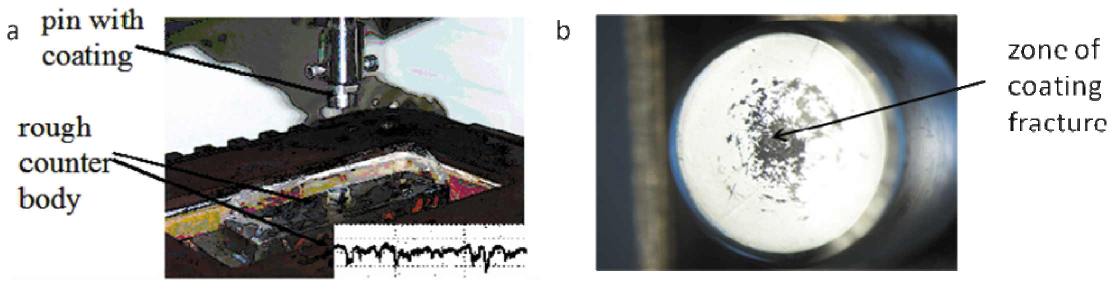

Fig. 4. (a) experiment conjunction and the counter body roughness; (b) photo of sample after friction test.

The next stage was the coatings testing in the range of contact loads from 4 to 15N, and also the calculation of the function $\Delta \tilde{\tau}_1(n)$, which characterize the maximum amplitude values of the principal shear stress for different loads. The calculation results for principal shear stresses under a die are presented in Fig.5. The maximum values of the stresses increase not only because of large load, but also because of mutual effect. But this effect decrease the amplitude value in comparison with the case of a single die with the same load conditions.

The result of the coatings testing was the coating fracture usually at the center of the sample (see Fig.4). The number of cycles at micro level before the fracture was from $35*10^7$ (for 4N load) to $1.8*10^7$ (for 15N load). The constants c and m were calculated from (12); the result is c=$1.4*10^{-22}$ and m=2.1. The accuracy of the estimation was 19%. This accuracy is not enough for reliable prediction of the coating fracture in different friction conditions; but it is possible to conclude that the relations (8)-(12) can be used for the modeling of interface damage accumulation .

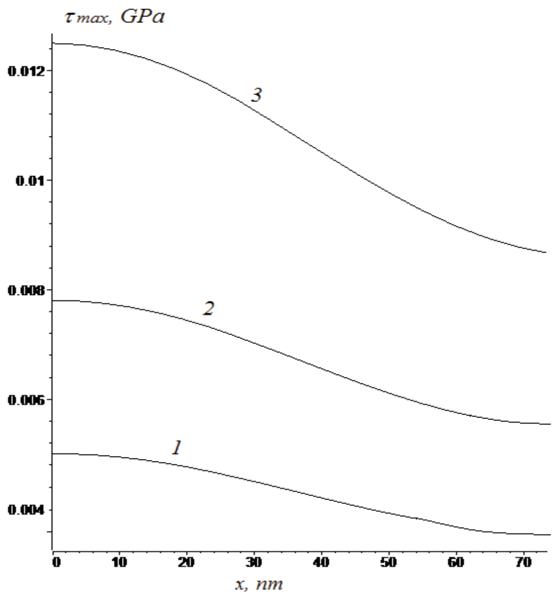

Fig. 5. Principal shear stresses at the layer-substrate interface for contact loads 4N, 6N, 10N (curves 1-3, respectively)

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