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**«Перспективные материалы с иерархической структурой
для новых технологий и надежных конструкций»**

**VIII ВСЕРОССИЙСКАЯ НАУЧНО-ПРАКТИЧЕСКАЯ
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«Добыча, подготовка, транспорт нефти и газа»

EFFECT OF ELASTIC GRADING ON FRETTING WEAR

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Fretting wear and fatigue represent a considerable problem in applications using frictional contacts subjected to vibrations as e.g. fretting of tubes in steam generators, joints in orthopaedics and dovetail blade roots of gas turbines. The physical reason for the fretting is partial sliding in the vicinity of boundary of a frictional contact. Tangential oscillations without slip would cause a stress singularity at the contact boundary; hence, for any finite coefficient of friction, there will be some slip region in the vicinity of the contact boundary. This partial slip and the resulting fretting wear can only be prevented by using a contact with sharp edges. However, in this case, both normal and tangential stresses will be singular at the boundary and oscillating stresses will lead to fretting fatigue. Thus, applications with frictional contacts under vibrations should find an optimal path between Scylla of fretting wear and Charybdis of fretting fatigue.

A possible solution of the wear/fatigue dilemma may be the use of functionally graded materials (FGM). The problem of fretting wear is due to the interplay of normal and tangential stresses. The distribution of the normal stresses is, however, governed by deeper parts of the material compared with tangential stress components. Changing the elastic modulus of the surface layer of the material or – more generally – introducing material gradients could help solving the dilemma.

Compared with other publications in the field, we concentrate our attention on the final shape which develops due to fretting wear and investigate this shape for power-law graded materials. We try to find the answer to the question, if it is possible to reduce or even completely exclude fretting wear by introducing gradients of elastic moduli.

The central idea of our approach to determine the limiting worn profile is very simple and robust. In [1], it was shown that, if two bodies are pressed against each other and subjected to small-amplitude tangential oscillations, the worn profile, independently of the particular wear or friction law, develops in time tending to some limiting shape, if the following assumptions are met:

- All deformations are predominantly elastic.
- Wear only occurs in the contact areas with non-vanishing relative displacement.
- Wear only occurs in the contact areas with non-vanishing pressure.
- The law of friction allows for the existence of a region of permanent stick.

Here we apply the idea introduced in [1] to analyse the limiting fretting shape of graded materials. We consider a contact of an axisymmetric rigid indenter with an elastic half-space, whose Young's modulus varies with depth according to the power law

$$E(z) = E_0 z^k, \quad -1 < k < 1, \quad (1).$$

where z is the vertical coordinate measured from the surface, E_0 is an arbitrary positive constant and k is the exponent ($k = 0$ corresponds to a homogeneous material).

As the final worn shape has to be achieved due to wear, the limiting profile of the indenter must exactly coincide with the form of the free surface produced by the initial indenter shape inside the permanent stick region. Thus, in the final state, in the slip region, the indenter and the elastic half space will be finally in the state of “incipient contact”. This logic does not depend on whether the material is homogeneous or heterogeneous, and it is not confined to axisymmetric contact configurations: The final worn shape is basically determined by the solution of the normal contact problem under the action of the profile defined only in the permanent stick region.

Fig. 1 shows the limiting profile shape in normalized variables for different values of k . The profile has been normalised for the indentation depth and the radial coordinate for the initial contact radius in the homogeneous case. In these variables the limiting profile only depends on k and the normalized fretting amplitude. We can easily recognize several features: first the contact radius is increasing with increasing k ; second the slip area is propagating slower from the edge of contact

Секция 4. Научные основы разработки материалов с многоуровневой иерархической структурой, в том числе для экстремальных условий эксплуатации

inside with increasing k ; finally the worn volume seems to decrease with increasing k . This, however, is only a part of the complete picture which is presented in detail in Fig. 2 (a,b) in form of “wear maps”. In these figures the total wear volume, normalized for the value in the homogeneous case, as a function of the two remaining parameters, the exponent k and the normalized fretting amplitude, is shown in contour isoline plots; the left hand side diagram (a) gives the semi-analytic solution based on the exact contact mechanical description, and the right hand side figure (b) shows the closed-form asymptotic solution for small fretting amplitudes.

For intermediate and large fretting amplitudes it is obviously beneficial to use a graded material with positive exponent k , i.e. a soft surface with a hard core. For negative k , i.e. hard surfaces, the wear volume is drastically increased. However, for very small oscillation amplitudes, it might be beneficial to use a grading with slightly negative k . Note, nonetheless, that the contact stresses in the case of negative elastic grading can be significantly increased if the hard surface is very thick and the soft core is isolated from carrying a relevant amount of the load. This will accelerate the wear process (although without changing the limiting profile if the indentation depth is prescribed) and may enhance fretting fatigue.

Fig. 1 Limiting profile shape after fretting normalized for the indentation depth as a function of the normalized polar radius for a parabolic indenter with radius R for different values of exponent k of the power-law grading. Normalized fretting amplitude is 0.5. Black line denotes the unworn profile.

Fig. 2 Contour isoline plots of the total worn-off volume normalized for the value in the homogeneous case for the fretting wear of a parabolic indenter on a power-law graded elastic half-space as a function of the exponent of elastic grading k and the normalized fretting amplitude. (a) Semi-analytic solution; black line denotes the transition to complete sliding. (b) Asymptotic solution for small fretting amplitudes.

1. Popov V.L. Analytic solution for the limiting shape of profiles due to fretting wear // Scientific Reports. 2014. № 4. 3749. DOI: 10.1038/srep03749.