SPECIAL FEATURES OF HIGH-FREQUENCY LOADING OF COATED MATERIALS

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We study the features of high-frequency loading of coated components: different combinations of stresses in the adhesive contact zone, which are caused by dynamic deformation of a base material and the action of body inertial forces, and the effect of cyclic loading on the adhesive and cohesive strength of a coating. We introduce the notion of “vibration strength” of a coating and show that it is essential to ensure an equal fatigue life of the base–coating system under cycling in an operating environment.

When in operation, coated components are subject to intensive alternating cyclic loads, including high-frequency ones. In the study of mechanical properties of coated materials, most of the attention was concentrated on the influence of coatings and the technological methods of their application on the strength of the base material under cyclic loading [1,2]. These studies were carried out mostly in the range of low frequencies of loading (0.1–200 Hz). The standardized frequency of loading ranges from 1 to 300 Hz [3]. In the case of low frequencies the body inertial forces are negligible. However, advanced engineering components have to operate in the high-frequency range. The frequency in the range from 18 to 20 kHz lies in the middle of the vibration spectrum conventionally encountered in the operation of advanced engineering components.

At high loading frequencies there arise body inertial forces. They depend on the amplitude of vibration, which may be the cause of failure of a coating in the antinode zone of vibration. The combination of stresses induced by dynamic deformation of a base material and by the body inertial forces, as observed between the node and antinode, may lead to cracking and peeling-off of the coating. In the case of such loading conditions, especially in a corrosive environment, we should both consider the effect of the coating on the cyclic strength of the base material and evaluate the adhesive and cohesive strength of the coating subjected to cyclic loading.

The standard [4] introduces the coefficient of the influence of surface hardening as a ratio of the endurance limits of hardened and nonhardened specimens but fails to clarify the mechanisms of fatigue fracture of a coating and breakdown of the adhesive contact zone. R. I. Stefanov [5,6] studied the influence of polymeric coatings on the fatigue characteristics of a base material by testing in air at a loading frequency of 10 kHz. For a number of coatings he observed an increase in the service life and the endurance limit of the base material while no fracture or peeling-off of the coating would occur. Other coatings failed well before the base material exhausted its lifetime. The cause of this failure was inadequate adhesive and cohesive strength of the coatings under cyclic loading.

Consequently, for dynamic loading we should introduce a concept that would characterize the adhesive and cohesive strength of coatings subjected to a short-time action of the body inertial forces combined with the strained state of the base material, as well as the fatigue adhesion and cohesion fracture of the coatings for the same combination. Thus, we define the concept of vibration strength.

We report here the experimental results illustrating the two above-mentioned features of the dynamic loading:

(1) the different combination of the stresses caused by dynamic deformation of a base material and body inertial forces, and

(2) the presence of adhesive and cohesive strengths of a coating under cyclic deformation.

We studied the vibration strength of a plasma-sprayed Al₂O₃ coating on steel 45 under longitudinal vibrations using an ultrasonic magnetostrictive vibrator. There was the possibility of an additional static loading of a specimen [7]. A steel 45 cylindrical rod 7.5 mm in diameter was subjected to longitudinal mechanical vibrations...
of amplitude $A_0 = 45 \mu m$ and frequency 18.8 kHz. The specimen working part included a quarter of the vibration wavelength $\lambda$ that ensured the presence of a node and antinode there ($\lambda = 70$ mm).

In this case, in the node we can observe a zero value of the amplitude and a maximum of deformation of the base material $|\varepsilon_0|$, while in the antinode the amplitude reaches its maximum $|A_0|$ and the deformation of the base material is zero, i.e., the amplitude and the deformation vary between the node and the antinode following the sine and cosine laws, respectively.

The Al$_2$O$_3$ coating of thickness $h = 110-250 \mu m$ was applied in the form of 5-mm-diameter circular elements (Fig. 1). We positioned these elements between the node and the antinode. This allowed us to develop different combinations of shear stresses over the contact zones and the deformation of the base material. We chose the size of adhesive contact elements so that the amplitude and the deformation of the base material are kept uniform over the contact zone to within the experimental error.

We calculated the dynamic deformation in the node by the following relationship [8]:

$$\varepsilon_0 = \omega A_0 \frac{\gamma_r}{\rho E}, \quad (1)$$

where $\omega$ is the angular frequency of vibration, $\gamma_r$ and $E$ are the density and elastic modulus of the rod, respectively.

The shear stresses due to the action of the body inertial forces at the coated element in the antinode zone were determined by the formula

$$\tau = \omega^2 A_0 h \gamma_c, \quad (2)$$

where $h$ is the thickness of the coating and $\gamma_c$ is the density of the coating material.

For intermediate adhesive sections in a zone between the node and antinode, we calculated the amplitudes $A_x$ and strains $\varepsilon_x$ by

$$A_x = A_0 \sin \frac{4x}{\lambda}, \quad (3)$$
$$\varepsilon_x = \varepsilon_0 \cos \frac{4x}{\lambda}, \quad (4)$$

where $x$ is the distance between the adhesive section and the vibration node. The shear stresses caused by the body inertial forces acting on various adhesive elements were evaluated from the amplitude $A_x$. Using expression (1), we obtain the strain value for the base material in the node $\varepsilon_0 = 0.102\%$. Figure 1 shows the shear stresses for each coating element.

All the coating elements survived the given dynamic loading at room temperature, and we could not raise the amplitude of vibration because of the cyclic strength of the base material. The coating did not fail even after $2.64 \times 10^7$ cycles.

We observed fracture of coating elements 1–4 (Fig. 1) after the static load component had been applied in combination with the dynamic one. The cracking was caused by the fact that the resultant of the dynamic $\varepsilon_d$ and static $\varepsilon_{st}$ strains exceeded the critical value $\varepsilon_{cr}$, which is $0.14\%$ for the Al$_2$O$_3$ coating with a porosity of 7–10\%. At coating element 5 the resultant strain does not exceed a critical value, which indicates that no fracture took place there.

In practice, there are coatings of much higher density and thickness, and thus higher body inertial forces are in effect in comparison with the coatings under study here. In that case, the shear stresses caused by the body inertial forces can overcome the cohesive strength with the resulting peeling-off of the coating.

The most widely accepted and promising method to protect material against a corrosive environment is to apply a coating on it. However, the cohesive and adhesive strength of the coating itself subjected to cyclic loading can be a weak point. This prevents one from taking full advantage of the cyclic strength of a base material. To evaluate the critical values of vibration strength of a protective coating, we should determine the cyclic strength of a base material under the conditions excluding the weakening action of the environment.