Research of mechanical characteristics thin coating

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Abstract: To solve many technical and economic problems, thin-walled coated structures are
created. Coatings are usually formed directly on curved surfaces of structural elements and
have a complex structure and complex surface relief. At the same time, some coatings are
almost impossible to dismember from the substrate.

An approach to study the stiffness properties of non-separable coatings on a thin-walled
substrate of complex shape, based on the fact that the tensile stiffness of the coating is equal to
the difference in the stiffness of the substrate with the coating minus the stiffness of the thin-
walled substrate. The experimental-theoretical method is used to estimate the stiffness. A
formula for estimating the Poisson's ratio for the initially flat version of the substrate in the
elastic formulation for cases of small deflection is obtained. An example of an assessment of
the hardness of the coating with the flat substrate. It was found that the stiffness of the coating
is 53.3 % of the substrate stiffness.

The approach is effective in the study of the mechanical properties of coatings, especially when
the stiffness of the coating and the substrate of the same order.

Introduction.

To solve technical and economic problems, in particular, friction and corrosion, protection from waves
and bacteria, etc., various coatings are used (Fig.1). Much attention is paid to functional and smart
coatings [1,2]. Based on the functional purpose and different requirements, are thin-walled structures
with a coating having a different shape – cylindrical, spherical, toroidal, etc. All the more common
construction, having an arbitrary shape (Fig.1).

![Figure 1. Complex structure element (a) with protective coating (b) ](image)

The coatings have different requirements, in particular, the hardness, the uniformity, continuity,
strength, adhesion, aging, deformability, etc. Coating, as a rule, are formed directly on the curved
surfaces of structural elements (Fig. 1). Various methods and methods of obtaining thin coatings on the substrate surface are used: ion-plasma and magnetron sputtering [3], laser cladding and ion implantation of the surfaces of structural elements, etc. It is not always possible to provide a given thickness of the coating, often there is a spread in thickness, for example, due to the heterogeneity of the deposition. At the same time, some coatings are almost impossible to dismember from the substrate.

Coatings in the process of operation acquire surface mechanical defects in the form of scratches and cracks or defects from interaction with the medium or physical field, which as stress concentrators, reduce their bearing capacity. To ensure the functional operation of the structure with a protective coating that is exposed to physical fields and environments, it is necessary to reliably determine both the initial mechanical properties of the coating and their change during operation.

The standard method of uniaxial tensile testing of strips of complex structure and shape samples is ineffective. The indenter method, which allows to judge the properties of the material in the vicinity of the considered point, is also not effective for complex structures, especially in the presence of nano and microdefects. The problem arises of determining the mechanical properties of coatings, including nanocoatings, without dismembering them from the substrate. The paper presents an experimental and theoretical approach to solving this problem.

An approach to study the stiffness properties of non-separable coatings on a substrate of complex shape. In cases where it is not possible to study the mechanical characteristics of the coating separately from the substrate, an approach can be used based on the fact that the tangential stiffness of the coating $B_{coat}$ under study is equal to the difference in the tangential stiffness of the thin-walled substrate with the coating $B_{sum}$ minus the tangential stiffness of the thin-walled substrate $B_{shel}$:

$$B_{coat} = B_{sum} - B_{shel}.$$  \hfill (1)

The experimental-theoretical method is used to estimate the tangential stiffness of the coated substrate $B_{sum}$ and the substrate $B_{shel}$.

At the experimental stage of the method, we obtain the dependence of the deformation of the object under study on the surface pressure. Alternately, we monitor the deformation of the fragment of the object under study (coated substrate or substrate only), clamped along the contour, from a uniform pressure applied to one of the surfaces of the object (Fig. 2). In particular, we obtain the relationship between the pressure $p$ and the maximum deflection $H$. It is also desirable to obtain the dependence of the thickness $h$ of the deflection $H$.

The jamming circuit may be different depending on the shape of the substrate. It is possible to use methods of investigation of mechanical properties of flat and spherical films and membranes [4,5]. In the study of arbitrary objects (Fig. 1) it is necessary to choose the most rational variant of the jamming circuit, which allows: at the experimental stage to provide effective jamming, and at the theoretical stage – to simplify the development of a numerical model.

At the theoretical stage of the method, we separately investigate the mechanical properties, in particular, the elastic modulus of the coated substrate and only the substrate. For plane and spherical
objects, we use the known dependences "pressure \( p \) - deflection \( H \)", obtained from the nonlinear theory of shells for the case of average bending [4,5]. In General, on the basis of known software systems, for example, ANSYS or the spline version of the finite element method [6], we develop a numerical model of the object under study.

Further, at each step of loading \( p \) by the method of "adjustment", varying the properties of the material – for example, for an elastic object by the elastic modulus \( E \) and the transverse compression coefficient (Poisson's ratio \( \nu \)), we approach the experimental parameters of the dome.

Thus, we determine the mechanical characteristics of the substrate, in particular the \( E_{\text{shel}}, \nu_{\text{shel}} \) and the substrate coated \( E_{\text{sum}}, \nu_{\text{sum}} \). Then the calculated tangential stiffness of the substrate thickness \( t_{\text{shel}} \) and the substrate is coated with a thickness of \( t_{\text{sum}} \)

\[
B_{\text{shel}} = \frac{E_{\text{shel}} t_{\text{shel}}}{1 - \nu_{\text{shel}}^2}, \quad B_{\text{sum}} = \frac{E_{\text{sum}} t_{\text{sum}}}{1 - \nu_{\text{sum}}^2}
\]

and we determine by (1) the tangential stiffness of the investigated coating \( B_{\text{coat}} \).

For the evaluation of Poisson's ratio \( \nu \) you can use the experimental parameters of the object of study in the testing process. So in the elastic formulation for the cases of small deflection (geometrically linear case) for the initially flat variant with a thickness \( h_0 \), for which it was not possible to obtain at the experimental stage the dependence of the thickness \( h \) on the deflection \( H \), we can use the formula

\[
\nu = \frac{aH}{\left( H^2 + a^2 \right) \arcsin \left( \frac{2aH}{H^2 + a^2} \right) + 3aH}
\]

This approach assumes no slippage of the coating relative to the substrate. The approach is effective for cases when the stiffness characteristics of the coating and substrate are of the same order.

**Example.** On the polymer film of PET thickness \( h_{\text{shel}} = 0.045 \) cm was applied by ion-plasma coating of titanium oxide \( \text{TiO}_2 \) thickness of about \( h_{\text{coat}} = 50 \) nm. The radius of the working part of the sample \( a = 4 \) cm. For fig.3 the image of the sample after the ETM test is presented.

Table 1 shows the deflections of the specimens \( H \) (mm) with coating and without coating, depending on the pressure \( p \), obtained experimentally-theoretical method [4,5]. The deflection of the samples corresponds to the case of an average bend. As you can see-the presence of the coating affects the deflections of samples.

Using Using the experimental data and relations [7] obtained from the nonlinear shell theory for the case of average bending according to The classification of H. M. Mushtari and the elastic deformation region, the tangential stiffness \( B \) of the formula is estimated

\[
B = Npa \left( \frac{a}{H} \right)^3
\]

where \( p \)-uniformly distributed pressure; \( a \)-the radius of the membrane; \( H \)-the deflection of the membrane in the center (the height of the dome). The values of \( N \) depending on the Poisson's ratio \( \nu \) are given in [7].

Table 1 also shows the change in the stiffness of the specimens in tension-compression \( B \) with coating (\( \nu=0.36 \)) and uncoated (\( \nu=0.4 \)) from the pressure \( p \). Also shown are the average values of the rigidities.

As can be seen from table 1, the tangential stiffness of the coated specimen is 1.53 times that of the uncoated specimen. The hardness of the coating \( B_{\text{coat}} = 344.19 \) kg / cm.
Table 1. Deflections of samples \( H \) depending on pressure \( p \)

| \( p \), MPa | The deflection of the sample \( H \), cm | The stiffness of the sample \( B \), kg/cm |
|-------------|---------------------------------|-----------------------------------|
|             | coated                          | without coating                   |
| 0.02        | 0.250                           | 0.287                             |
|             | 977.61                          | 633.72                            |
| 0.05        | 0.336                           | 0.373                             |
|             | 1006.72                         | 721.71                            |
| 0.08        | 0.394                           | 0.433                             |
|             | 998.98                          | 738.14                            |
| 0.12        | 0.455                           | 0.496                             |
|             | 972.98                          | 524.48                            |

Average sample stiffness values: \( B_{sum} = 989.07 \) \( B_{shel} = 645.51 \)

**Figure 3.** The sample after the test

**Figure 4.** Based on the stiffness of the samples with coating B (a) and without coating (b) from the pressure \( p \)

**Conclusions:** The experimental-theoretical approach is an effective method of studying the properties of thin coatings. The approach is clear and simple, there is no need to dismember the coating from the substrate. The approach should find its place both in the study of the mechanical properties of the newly created coatings, as well as to study the changes in the properties of coatings during operation.

**References**

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