Determination of hardness of thin layer coating and its adhesion to the shell of the cylindrical form

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Abstract. On the basis of coatings a lot of technical and economic problems are solved. Functional and smart coatings are developed, which are formed directly on the curvilinear surfaces of structural elements. An experimental-theoretical method for evaluating the stiffness properties and adhesion of a thin-layer coating of a complex structure formed on a cylindrical surface is developed. The method is a reliable tool both for determining the mechanical properties of a coating and an adhesive, and for studying the effect of physical fields and media on changing these properties. An example of a study is considered.

1. Introduction

Film and membrane coatings are widely used in all industries and life. On the basis of coatings solve problems: friction and wear, corrosion and erosion, wave absorption, protection from fire, viruses and bacteria, etc. (Figure 1).

Various coatings and adhesion components are created. In recent years, great attention has been paid to the creation of functional and smart coatings. The necessary qualities of coatings are provided by the development of complex composite structures and adhesive, which are formed directly on the curvilinear surfaces of structural elements [1-3].
To ensure the functional operation of the structure with a protective coating, which are affected by physical fields and media, it is necessary to reliably determine both the initial mechanical properties of the coating and the adhesive, and their variation during operation. It is impossible to investigate the mechanical properties of coatings of complex structure and shape by a standard uniaxial method. Also, the method of the "indenter" is ineffective in the study of such coatings.

Experimental-theoretical methods for investigating the stiffness properties of planar and spherical thin-walled elements of structures of complex structure [4,5] and adhesion of a film to a flat substrate are known [6,7].

There is a need to create an effective method (tool) for diagnosing the condition of the initially non-planar coating and its adhesion to the structural element. Such a tool is necessary both at the design stage and at the stage of structural exploitation, as well as for studying the regularities of changing the properties of the coating and adhesive under the influence of media, physical fields and operational factors.

An experimental-theoretical method for determining the stiffness properties and adhesion of a thin-layer coating of a complex structure formed directly on a cylindrical surface is developed. An example of a study is considered.

2. Experimental-theoretical method for determining the stiffness and adhesion of a coating to a cylindrical shell

The device for testing (Figure 2) consists of a set of closed cylindrical tanks of different diameters (1), a pressure source of the working medium (2) with a pressure gauge (3), a manifold with a valve for supplying the working medium (4), a measuring complex (5) and line for etching the working medium (6).

On the lateral surface of the cylindrical tanks (1) there is an opening - in this region a coating is placed (formed according to a given technology). The parameters of the formed dome are also given there: the deflection $H$ and the parameters of the elliptic base of the dome $a$, $b$.

At the first stage, we investigate the rigid properties of the coating. We supply the pressure stepwise into the tank (1). At each loading step $p$, we monitor the shape of the deformation of the coating under pressure $p$, measure the dome parameters: $a$, $b$ and $H$. We obtain the dependence "deflection $H$ - pressure $p" for the dome top

$$H = f(p).$$

Next, we develop numerical models of deformation of a fragment of a cylindrical covering of an elliptical shape in a plan using known grid methods and software complexes (for example, ANSYS or a spline version of the finite element method based on three-dimensional finite elements [8]).

At each step of loading $p$, by the method of "adjustment" - by varying the properties of the material, for example, for an elastic covering by the elasticity modulus $E$ and the Poisson's ratio,
approaching the parameters of the dome corresponding to the experimental parameters \( H, a, b \), while determining the distribution of the stress-strain state of the coating; if necessary, we construct the curves "modulus of elasticity - deformation". Thus, we determine the mechanical characteristics of the coating under investigation.

In the second stage, we investigate the adhesion properties of the coating to a cylindrical surface. In the problem under consideration, the emerging forces of detachment of the coating along the contour change significantly. Therefore, within the framework of the grid under consideration, we determine the local value of the clutch stress normal to the cylindrical surface \( \eta_{otr} \) with formula:

\[
\eta_{otr} = T_{otr} / S_{otr}, \quad S_{otr} = h_0 (1 - \varepsilon_1 - \varepsilon_2),
\]

(2)

where \( S_{otr} \) is the coverage area along the contour of unit length in the local region of the separation line, \( h_0 \) is the thickness of the coating before deformation; \( \varepsilon_1, \varepsilon_2 \) is the deformation of the covering in the normal and tangential directions near the contour.

The normal detachment forces \( T_{otr} \) are calculated by the formulas:

\[
T_{otr} = T_1 \frac{ab \sqrt{R^2 \left(b^2 \cos^2 \theta + a^2 \sin^2 \theta\right) - a^2 b^2 \sin^2 \theta}}{RR \left(b^2 \cos^2 \theta + a^2 \sin^2 \theta\right)}
\]

(3)

\[
R = \frac{2R \Delta z - \Delta z^2 + (H + \Delta z)^2 \sin \theta}{2(H + \Delta z) \sin \theta}, \quad \Delta z = \frac{a^2 b^2 \sin^2 \theta}{\sqrt{\left(b^2 \cos^2 \theta + a^2 \sin^2 \theta\right) R^2 - a^2 b^2 \sin^2 \theta (b^2 \cos^2 \theta + a^2 \sin^2 \theta)}},
\]

where \( T_1 \) the tangential forces in the film normal to the contour in the local detachment region, which are determined in the first stage of the problem.

**Example**

A metal cylindrical shell with an outer radius \( R_c = 174 \) mm with a coating of a polymer material of thickness \( h_0 = 0.17 \) mm is considered. The diameter of the hole in the cylindrical shell is \( d = 5.5 \) mm. The experimental data for \( p = 0.19 \) MPa are given in Table 1.

| Table 1 - Experimental data |
|-----------------------------|
| \( p \), MPa | \( H \), mm | \( 2a \), mm | \( 2b \), mm |
| 0.19 | 0.29 | 14.0 | 13.0 |

A fragment of the installation with a coating on a container of cylindrical shape is shown in Fig. 3, and the finite-element model of the coating based on the element SOLID186 (the training version of ANSYS) in the dome area is shown in Fig. 4.

According to the "alignment" data at the first stage, the problems were obtained - the modulus of elasticity of the coating \( E_{max} = 25000 \) MPa, \( \nu = 0.4 \). Figure 5 shows the movement of the coating along the \( z \) axis, at which the maximum displacement was \( 0.296 \) mm, and in the experiment \( H = 0.29 \) mm, i.e. "alignment" with an error of about 2%.

The distribution of stress intensity on the outer and inner surfaces of the coating is shown in Fig. 6a and Fig. 6b, respectively. From Fig. 6 shows the complex nature of the stress intensity distribution. At the same time, the stress state of the outer and inner surfaces of the coating is significantly different.
In Fig. 7 shows the distribution of stress intensity along the contour of the coating - only a quarter of the contour is considered from the symmetry condition.

Then, using formulas (2) and (3), we calculate the resulting tearing forces $\text{T}_{\text{otr}}$ and the normal bonding stresses $(\sigma_{\text{otr}}$ along the contour (Table 2).

As can be seen from Table 2, the adhesion stresses $\eta_{\text{otr}}$ along the contour, vary significantly with the angle $\Theta$. 

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**Fig. 3** - a fragment of the installation - a cylindrical shell with a coating

**Fig. 4** - finite-element of coverage

**Fig. 5** - picture of the movement of the coating along the $z$ axis

**Fig. 6** - the intensity of overlap along the outer a and inner b surfaces
Fig. 7 - intensity of stress along the contour of the coating

Table 2 - Calculated data

| \( \Theta \) | \( T_1 \), MPa mm\(^2\) | \( T_{otr} \), MPa mm\(^2\) | \( \eta_{otr} \), MPa |
|---|---|---|---|
| \( 0^\circ \) | 9.537 | 0.4478 | 1.49 |
| \( 15^\circ \) | 10.413 | 0.6437 | 2.15 |
| \( 30^\circ \) | 11.376 | 0.9263 | 3.09 |
| \( 45^\circ \) | 12.690 | 1.2723 | 4.24 |
| \( 60^\circ \) | 13.216 | 1.5011 | 5.00 |
| \( 75^\circ \) | 14.004 | 1.6575 | 5.52 |
| \( 90^\circ \) | | | |

Conclusion
An experimental theoretical method for determining mechanical characteristics and adhesion of a coating of a complex structure formed directly on a cylindrical shell has been developed. The method is a reliable tool both for evaluating the mechanical properties of the coating and the adhesive, and for studying the effect of physical fields and media on changing these properties.

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