Investigation of the influence of the nature of surface deformation on coating adhesion

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Abstract. The effect of deformation of the surface of a supporting metal element on the adhesion of a thin polymer film has been studied by an experimental-theoretical method. A setup has been developed that allows testing of adhesive coatings at various deformations of the substrate surface of various materials. The adhesion properties of a polymer film to a metal substrate have been determined. An explanation of the results obtained is given.

1. Introduction

The problem of ensuring the trouble-free operation of structures exposed to physical fields and environments is one of the main problems of our time. It is especially important for chemical, petrochemical, energy and other enterprises, where the problems of ensuring technical and environmental safety are especially acute. To ensure the operability of the structure and prevent its destruction, it is necessary to maintain its constituent elements in a working condition [1]. One of the global and effective directions for solving this problem is the use of various protective coatings. By imitating natural structures, a person creates various functional and smart coatings. In this case, the quality of the coatings is ensured by the development of complex thin-layer composite structures and adhesive [1–4].

During the operation of structures as a result of the influence of the environment and physical fields, as well as the human factor, changes in the mechanical and physical characteristics of coatings and adhesive occur. As a result, the protective coatings fail, leading to the loss of the supporting structures function. There is a need to assess the mechanical properties of coatings and adhesive, as well as to study the regularity of changes in these properties under the influence of environment and physical fields, including the deformation ones.

In this work, the effect of deformation of the surface of a supporting metal element on the adhesion of a thin polymer film has been investigated by the experimental-theoretical method.

2. The research setup and the method for assessing adhesion

To study the effect of surface deformation on the adhesion of the coating, a special setup has been developed, the diagram of which is shown in figure 1, and the fragments of the setup in the process of testing the adhesion of the coating are shown in figure 2.
The setup consists of a rectangular plate made of a substrate material 1. The plate can be composite, consisting of a common metal plate, to which a thin plate of the substrate material is attached. There is a hole for air supply in the central part of the plate. Angles 6 with holes are attached to the narrow opposite edges of the plate, on which two rods 7 (tightening the setup) are attached to create a compressive force. By adjusting the length of the rod, the plate is bent to the required amount (up to the set \( H \) of the lifting boom). The setup consists of the compressed air supply unit 4 with appropriate pipelines and fittings, as well as of a measuring unit 3, which includes indicators, a ruler for measuring linear dimensions, a pressure gauge 5, and photographic equipment. Measurements of the diameter of the exfoliated part of the film are made either by the contact or a non-contact method. For the non-contact method, the optical devices are used either a camera or a video camera. The observation with measurements is carried out visually by video filming (or photography), or direct measurement of the required dimensions. Photo and video information is transferred to digital media. To improve the accuracy of measuring the ratio of geometric dimensions the photographs of an enlarged format are used.

The setup allows testing the adhesion properties of coatings at various deformations of the substrate surface made of various materials, i.e. to investigate adhesion in various combinations of constituent elements in the "substrate - coating" system.

The methods for determining the adhesion of the coating to the substrate are shown in [5–8], each of which has certain disadvantages. The experimental - theoretical approach is effective and simple [9].

At the experimental stage, coating 2 is applied or glued to the surface of the plate (substrate), in accordance with a predetermined technology, 2. The substrate is deformed by a tightening device to a...
given lifting boom H, connected to the air supply unit 4 and fixed on the table surface. Then a peeling load is applied to the coating 2 by supplying the internal pressure of the working medium from 4 through the hole in the substrate and the monitoring of the geometric parameters of the formed dome under the influence of pressure is made, in particular, measuring the diameter of the dome base d and the height of the dome rise h.

At the theoretical stage, according to [9], in the first approximation, the specific force required to detach a unit area of the sample from the substrate (adhesion) is determined - the adhesion stress \( \eta_{i+1} \) at the \((i+1)\)-th stage of loading with a surface load \( p_{i+1} \) from the condition of static equilibrium dome:

\[
\eta_{i+1} = \frac{5}{16} \frac{p_{i+1} d_{i+1}}{d_{i+1} - d_i}
\]  

(1)

where \( \eta_{i+1} \) is the current adhesion stress characterizing the adhesion strength of the sample to the substrate; \( d_i \) and \( d_{i+1} \) are the diameters of the dome base at two adjacent states of pressure of the working medium; \( p_{i+1} \) - uniformly distributed pressure of the working medium with the diameter of the dome base \( d_{i+1} \).

Formula (1) was derived under the assumption that the stress along the radius of the ring of the delamination surface, starting from the edge, is distributed along a fourth-order parabola:

\[
\sigma = - \frac{\sigma_m}{(d_{i+1} - d_i)^4} r^4 + \sigma_m,
\]  

(2)

and the average stress along the delamination ring is determined by the formula:

\[
\sigma_{sr} = \frac{1}{d_{i+1} - d_i} \int_0^{d_{i+1} - d_i} \sigma dr = \frac{4}{5} \sigma_m.
\]  

(3)

where \( \sigma_m \) is the stress on the edge, at the beginning of the movement is equal to the adhesion stress \( \eta_{i+1} \) (adhesion strength).

Further, after calculating \( \eta_{i+1} \) according to (1), the average value of adhesion - stress (strength) of adhesion \( \eta_{sr} \) is determined and the conclusion is made about the strength of adhesion (adhesion) of the coating to the substrate.

The method allows, in the first approximation, to investigate the adhesion properties of a wide range of different combinations of coatings and substrates and to obtain stable results for relatively hard coatings.

When determining the adhesion strength \( \eta_i \) of flexible coatings to the substrate, expression (1) is refined by the formula:

\[
\eta_{i+1} = \frac{5}{16} \frac{p_{i+1} d_{i+1}}{d_{i+1} - d_i} \frac{d_i^2}{h_{i+1}^2 + h_{i+1}}
\]  

(4)

where \( h \) is the height of the dome rise.

3. Investigation of the effect of the nature of deformation on the adhesion of the coating to the substrate

According to the method described above, the adhesion properties of a polymer coating to a metal substrate were determined. An aluminum alloy plate with the following parameters was considered: length \( L = 82.4 \) cm, width \( B = 10 \) cm, thickness \( t_{pl} = 0.3 \) cm; the diameter of the central hole is \( d_{at} = 0.8 \) cm. A wide adhesive tape with a thickness of \( t_{pk} = 0.005 \) cm was used as a film. For the deformed plate, the lifting arrow was \( H = 2.8 \) cm.

From the experiment, the dependences of the height of the dome rise \( h \) (cm) and the diameter of the dome base \( D \) (cm) on the pressure \( p \) (MPa) were obtained. Then in the pressure range from 0.044 MPa
to 0.069 MPa, the adhesion properties were calculated using formulas (1) and (4), the average values of which are given in Table 1.

Table 1. Adhesion of the coating to the substrate, depending on the nature of its deformation.

| Surface deformation | $\eta_1$, MPa (1) | $\eta_{111}$, MPa (4) |
|---------------------|-------------------|----------------------|
| No deformation      | 1,453             | 1,442                |
| Stretched surface   | 1,225             | 1,219                |
| Compressed surface  | 0,957             | 0,953                |

As can be seen from table 1, the presence of deformation of the plate surface reduces the adhesion strength, and in this case effect is more significant on a compressed surface.

4. Conclusions
The phenomenon of a decrease in the adhesion strength of the film to the coating is explained by the fact that when the substrate is deformed into the coating (in the film), the tangential deformations occur, creating additional tearing stresses; on compressed surfaces in the coating the additional stresses arise due to the tendency of the coating to form corrugation, therefore the effect of reducing the adhesion strength of the film to the coating is more significant.

References
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