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Experimental-Theoretical Method for Assessing the Stiffness and Adhesion of the Coating on a Spherical Substrate

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The authors declare that there is no conflict of interest.

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Abstract. Known methods and approaches are ineffective or not applicable at all in the study of mechanical characteristics and adhesion of coatings of complex structure, initially formed on non-planar surfaces. A device has been developed that includes fragments of spherical substrates with rings for mounting along the contour, a pressure source of the working medium with a pressure gauge, a line with a valve for supplying the working medium, a measuring complex and a line for etching the working medium. In a fragment of a spherical substrate there is a small diameter hole, in the area of which a cover is formed according to a given technology. The working medium is fed through a small hole in the tray. A segment of the coating detached from the substrate forms a dome in the form of an ellipsoid fragment. A numerical model of deformation of a coating fragment in the form of a spherical segment with a complex contour is being developed using well-known software complexes. At each step of loading by the "targeting" method, varying the modulus of elasticity and the Poisson's ratio, we approach the parameters of the experimental dome and determine the actual mechanical and stiffness properties of the coating under study. We calculate the normal separation forces through the radial forces determined by the current numerical model, and then determine the coupling stresses. The developed experimental-theoretical method is an effective tool for evaluating the mechanical properties and stiffness of coatings of complex structure, as well as the adhesion of the coating to a spherical substrate.

Keywords: complex structure, adhesive, coating stiffness, adhesion stresses

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Экспериментально-теоретический метод оценки жесткости и адгезии покрытия на сферической подложке

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Заявление о конфликте интересов
Авторы заявляют об отсутствии конфликта интересов.

Вклад авторов
Нераздельное соавторство.

Аннотация. Известные методы и подходы, исходно сформированные на неплоских поверхностях, малоэффективны или вовсе неприменимы при исследовании механических характеристик и адгезии покрытий сложной структуры. Разработано устройство, включающее фрагменты сферических подложек с кольцами для крепления по контуру, источник давления рабочей среды с манометром, магистралью с вентилем для подачи рабочей среды, измерительного комплекса и магистрали для травления рабочей среды. Во фрагменте сферической подложки имеется отверстие малого диаметра, в области которого формируют покрытие по заданной технологии. Через небольшое отверстие в подложке подается рабочая среда. Оторванный от подложки сегмент покрытия образует купол в виде фрагмента эллипсоида. Разрабатывается численная модель деформирования фрагмента покрытия в виде шарового сегмента со сложным контуром, используя известные программные комплексы. На каждом шаге нагружения методом «пристрелки», варьируя модулем упругости и коэффициентом Пуассона, приближаемся к параметрам экспериментального купола и определяем актуальные механические и жесткостные свойства исследуемого покрытия. Вычисляем нормальные усилия отрыва через радиальные усилия, определенные по актуальной численной модели, и определяем далее напряжения сцепления. Разработанный экспериментально-теоретический метод является эффективным инструментом оценки механических свойств и жесткости покрытий сложной структуры, а также адгезии покрытия к сферической подложке.

Ключевые слова: сложная структура, адгезив, жесткость покрытия, напряжения сцепления

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1. Introduction

One of the most developed approaches for protecting surfaces from environmental influences is coating. Surface coatings are widely used in all branches of production and life [1–3]. They provide protection and insulation of the surface of structures operating in various environments and under the influence of various physical fields.

Based on the operating conditions, various coatings and adhesives of complex structure are developed, providing the necessary qualities [4–8]. Active work is underway to create functional and intelligent coatings for corrosion protection [9–15].

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During the operation of structures, protective coatings fail first of all, which can lead to serious consequences, in particular, to intensive corrosion wear of the bearing elements of the structure. When choosing a coating, adhesive and its application technology, questions arise related to determining their necessary parameters, evaluating their mechanical properties and their service life depending on operating conditions.

Methods for evaluating the mechanical properties of coatings. Various approaches are used to study the mechanical characteristics of coatings [6–8]. The indenter method [16], which allows determining the properties of a material in the vicinity of a given point, has become widely used. There are studies based on the molecular approach [17], in which difficulties arise in describing the structure of the coating at the molecular level. However, for coatings of complex structure, the indenter method and the molecular approach are ineffective. There is a large variation in the results of the study by the standard uniaxial tensile testing method of coatings of a complex structure in the shape of a rectangle based on the Russian state standard GOST 14236-81. Polymer films. Tensile Test Method; ASTM D 412-41.

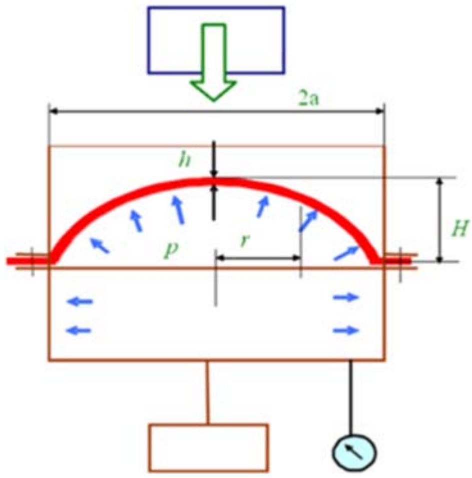

Figure 1. Fragment and installationdiagram
Source: made by N.M. Yakupov

An effective approach to assessing the mechanical properties of films is the experimental — theoretical ETM method [18], which allows evaluating the integral properties of coatings. ETM is based on the synthesis of experimental data and relations from the theory of thin shells. Figure 1 shows a diagram of the device. The installation allows testing of round-shaped samples in plan.

The sample is placed on the device, loaded with a uniform surface pressure p and the form of deformation of the sample is monitored. The dependence "pressure p — deflection H" is obtained from the experiment, and then, using the relations of the theory of shells, the mechanical properties of the coating are determined [18].

Methods for assessing the adhesion of coatings. Various methods have been developed to determine the adhesion strength of the coating to the substrate. There are, for example, USSR copyright certificate No. 183459; RF patents No. 689411, No. 2207544. These developments have some disadvantages, in particular, technological difficulties and do not provide the necessary accuracy. A method is known for estimating the adhesion of an elastic coating to a substrate based on the parameters of the "bubble" [19].

A method has been developed for determining the adhesion of rigid and flexible coatings to the substrate (RF Patent No. 2421707), which allows assessing the adhesive properties taking into account the mechanical characteristics and thickness of the coating (Figure 2). At the same time, the spread of results is reduced.

Modern coatings have a complex structure and are formed, as a rule, directly on the surfaces of structures of various shapes, in particular, on cylindrical, spherical and toroidal surfaces [20]. Known methods and approaches are ineffective or completely inapplicable in the study of the mechanical characteristics of coatings of complex structure, initially formed on non-planar surfaces.

The purpose of this work is to develop an effective tool for determining the stiffness properties of coatings of complex structure and adhesive on a spherical substrate.

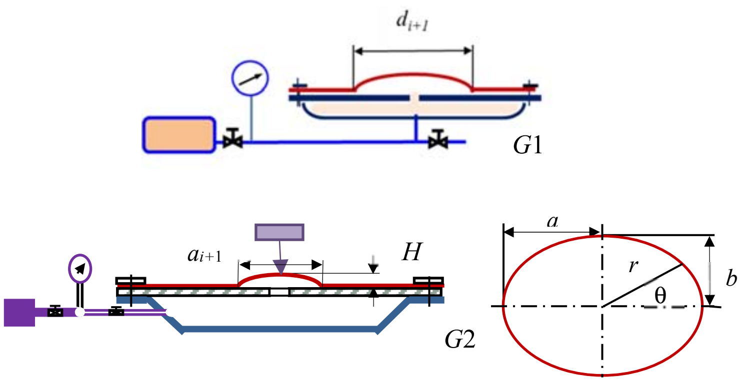

Figure 2. Installation diagrams: *G*1 — for rigid coatings; *G*2 — for flexible coatings
Source: made by N.M. Yakupov

2. Method for assessing the adhesion of the coating on a spherical substrate

The test device consists of a set of fragments of spherical substrates of various diameters, a pressure source of the working medium with a pressure gauge, a line with a valve for supplying the working medium, a measuring complex and a line for etching the working medium. There is a small diameter hole in the substrate, in the area of which a coating is formed according to a given technology. A fragment of the installation diagram is shown in Figure 3.

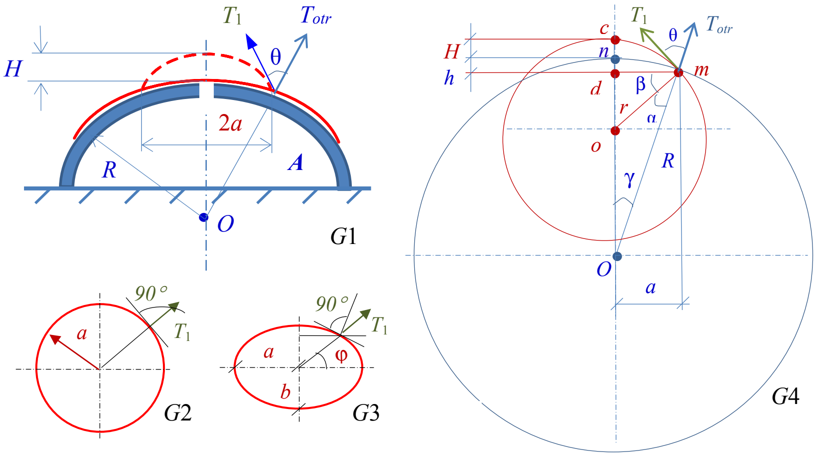

Figure 3. Diagram of the experimental setup (*G*1); dome parameters:
the base of the spherical segment (*G*2), the base of the ellipsoid fragment in plan (*G*3),
the diametrical section of the spherical segment (*G*4)
Source: made by N.M. Yakupov

The algorithm of the method. During the experiment, the working medium, in particular, air, is smoothly fed into the inner cavity of the spherical substrate — cavity *A* (Figure 3, *G*1). When the pressure reaches a certain value, the coating slowly comes off. At the same time, a dome is formed. In the simplest case, a dome is formed in the form of a spherical segment with radius r (axisymmetric variant) with a flat base in the form of a circle with radius a (Figure 3, *G*2). In a more general case, a dome is formed that is close in shape to an ellipsoid fragment; at the same time, the base of the dome is a spatial curve lying on a spherical surface of radius *R* and having in plan a shape close to an ellipse with semi-axes *a* and *b* (Figure 3, *G*3).

At the first stage, the stiffness property of the coating is investigated. At each step of loading p, the form of deformation of the coating under pressure p is monitored, the dome parameters are measured: a, b and H. Next, numerical models of deformation of a coating fragment in the form of a spherical segment with radius r, in a particular case, or in the form of an ellipsoid fragment having a shape close to an ellipse with semi-axes a and b are developed . In this case, either well-known software systems, for example, ANSYS, or a spline version of the finite element method (CB FEM) are used [21; 22].

At each step of loading p by the “targeting” method, varying the properties of the material, for example, for an elastic coating with the elastic modulus E_j and the Poisson's ratio ν_j, we approach the dome parameters corresponding to the experimental parameters a, b and H. The mechanical parameters E and ν, at which the maximum approximation of the numerical model to the experimental shape of the dome is observed, characterize the actual mechanical properties of the coating under study. Further, if necessary, it is possible to calculate the stiffness of the coating for stretching B and bending D:

$$B = \frac{Eh}{(1-\nu^2)}; \quad D = \frac{Eh^3}{12(1-\nu^2)}. \tag{1}$$

Thus, we determine the actual mechanical properties of the coating under study and determine the stress-strain state of the coating. At the same time, special attention is paid to the determination of tangential forces T_1 and deformation of the coating, in the radial (normal) ε_1 and tangential ε_2 directions near the contour of the dome.

At the second stage, we investigate the adhesive properties of the coating to the spherical surface of the substrate. Based on the radial forces

At the second stage, we investigate the adhesive properties of the coating to the spherical surface of the sub-strate. Based on the radial forces T_1 obtained at the first stage, we determine the normal separation forces T_{otr}.

For a dome in the form of a spherical segment, based on Figure 3, the separation forces are the same along the entire contour and can be determined by the formula:

$$T_{otr} = T_1 \frac{2a(H+R-\sqrt{R^2-a^2})(\sqrt{R^2-a^2}-\sqrt{r^2-a^2})}{R[(H+R-\sqrt{R^2-a^2})^2+a^2]}. \quad (2)$$

For the more general case, the contour separation forces vary depending on the parameters a and b. However, if we take into account that the maximum forces of separation of the coating will be in the area of the small semi-axis b, then the separation forces can be determined by the formula:

$$T_{otr} = T_1 \frac{2b(H+R-\sqrt{R^2-b^2})(\sqrt{R^2-b^2}-\sqrt{r^2-b^2})}{R[(H+R-\sqrt{R^2-b^2})^2+b^2]}. \quad (3)$$

Further, according to certain normal separation forces T_{otr}, determine the coupling tension η_{otr} by the formula:

$$\eta_{otr} = \frac{T_{otr}}{h_0(1-\varepsilon_1-\varepsilon_2)}. \quad (4)$$

Performing the procedure for calculating the coupling voltage $\eta_{otr}(p_i)$ according to this algorithm for a number of pressures p_i $(i = 1 \div n)$, we determine the average values $\boldsymbol{\eta_{otr\text{-}sr}}$ by the formula:

$$\eta_{otr\text{-}sr} = \left(\sum \eta_{otr}(p_i)\right) / n. \quad (5)$$

3. Conclusion

1. A coating of a complex structure, initially formed on a fragment of a spherical substrate, is investigated. The working medium was fed through a small hole in the substrate. A segment of the coating torn from the substrate formed a dome in the form of an ellipsoid fragment.
2. A numerical model of deformation of a coating fragment in the form of a spherical segment has been developed using well-known software systems. At each step of loading by the “targeting” method, varying the modulus of elasticity and the Poisson’s ratio, when approaching the parameters of the experimental dome, the actual mechanical and stiffness properties of the coating under study were determined. According to the radial forces determined by the current numerical model, the normal separation forces are calculated and the coupling stresses are determined.

The developed experimental-theoretical method is an effective tool for assessing the mechanical properties and rigidity of coatings of complex structure, as well as the adhesion of the coating to a spherical substrate.

References / Список литературы

1. Dry C. Procedures developed for self-repair of polymeric matrix composite materials. *Composite Structures.* 1996;35(3):263–269. https://doi.org/10.1016/0263-8223(96)00033-5

2. Montemor M.F. Functional and smart coatings for corrosion protection: A review of recent advances. *Surface and Coatings Technology.* 2014;258:17–37. https://doi.org/10.1016/j.surfcoat.2014.06.031

3. Yakupov S.N., Yakupov N.M. Research of mechanical characteristics thin coating. *Scientific Technical Conference on Low Temperature Plasma during the Deposition of Functional Coatings 5–8 November 2018, Kazan University, Kazan, Russian Federation. Journal of Physics: Conference Series.* 2019;1328:012103. https://doi.org/10.1088/1742-6596/1328/1/012103

4. Sripada J.V.S.N., Saha D.C., Saha G.C., Jahed H. Bonding mechanism and mi-crostructural evolution in mechanically-alloyed nanodiamond-reinforced Al6061 composite particle deposits in cold spray. *Surface and Coatings Technology.* 2023;466:129611. https://doi.org/10.1016/j.surfcoat.2023.129611

5. Bochenek K., Węglewski W., Morgiel J., Basista M. Influence of rhenium addition on microstructure, mechanical properties and oxidation resistance of NiAl obtained by powder metallurgy. *Materials Science and Engineering: A.* September 2018;735:121–130. https://doi.org/10.1016/j.msea.2018.08.032

6. Liu S., Wu H., Xieetal X. Tribological properties of cold-sprayed 7075Al coatings reinforced with hybrid nano-TiB2/micro-SiC particles. *Surface and Coatings Technology*. 2023;458:129323. https://doi.org/10.1016/j.surfcoat.2023.129323

7. Maurya S.S., Pandey K.K., Sharma S., Kumari S., Mirche K.K., Kumar D., Pandey S.M., Keshri A.K. Microstructural, mechanical and tribological behavior of nanodiamonds reinforced plasma sprayed nickel-aluminum coating. *Diamond and Related Materials.* 2023;133:109714. https://doi.org/10.1016/j.diamond.2023.109714

8. Awotunde M.A., Olubambi P.A., Chen D. Compressive deformation behaviour and toughening mechanisms of spark plasma sintered NiAl-CNT composites. *Ceramics International.* 2022;48(11):16072–16084. https://doi.org/10.1016/j.ceramint.2022.02.153

9. Ahmad S., Gupta A.P., Sharmin E., Alam M., Pandey S.K. Synthesis, characterization and development of high performance siloxane-modified epoxy paints. *Progress in Organic Coatings*. 2005;54(3):248–255. https://doi.org/10.1016/j.porgcoat.2005.06.013

10. Qian M., Soutar A.M., Tan X.H., Zeng X.T., Wijesinghe S.L. Two-part epoxy-siloxane hybrid corrosion protection coatings for carbon steel. *Thin Solid Films.* 2009;517(17):5237–5242. https://doi.org/10.1016/j.tsf.2009.03.114

11. Xue D., Van Ooij W.J. Corrosion performance improvement of hot-dipped galvanized (HDG) steels by electro-deposition of epoxy-resin-ester modified bis-[tri-ethoxy-silyl] ethane (BTSE) coatings. *Progress in Organic Coatings.* 2013; 76(7-8):1095–1102. https://doi.org/10.1016/j.porgcoat.2013.03.004

12. Diaz I., Chico B., de la Fuente D., Simancas J., Vega J.M., Morcillo M. Corrosion resistance of new epoxy-siloxane hybrid coatings. A laboratory study. *Progress in Organic Coatings.* 2010;69(3):278–286. https://doi.org/10.1016/j.porgcoat.2010.06.007

13. Holness R.J., Williams G., Worsley D.A., McMurray H.N. Polyaniline Inhibition of Corrosion-Driven Organic Coating Cathodic Delamination on Iron. *Journal of The Electrochemical Society.* 2005;152(2):B73. https://doi.org/10.1149/1.1850857

14. Hosseini M.G., Jafari M., Najjar R. Effect of polyaniline–montmorillonite nanocomposite powders addition on corrosion performance of epoxy coatings on Al 5000. *Surface and Coatings Technology.* 2011;206(2–3):280–286. https://doi.org/10.1016/j.surfcoat.2011.07.012

15. Zhang X., He Q., Gu H., Colorado H.A., Wei S., Guo Z. Flame-retardant electrical conductive nanopolymers based on bisphenol F epoxy resin reinforced with nano polyanilines. *ACS Application. Material. Interfaces.* 2013;5:898–910. https://doi.org/10.1021/am302563w

16. Oliver W.C., Pharr G.M. An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments. *Journal of Materials Research.* 1992;7:1564–1583. https://doi.org/10.1557/JMR.1992.1564

17. Yanovsky Yu.G., Nikitina E.A., Nikitin S.M., Karnet Yu.N. Quantum mechanical studies of the mechanism of deformation of carbon nanotubes. *Mechanics of Composite Materials and Structures.* 2009;15(3):345–368. (In Russ.)

Яновский Ю.Г., Никитина Е.А., Никитин С.М., Карнет Ю.Н. Квантово-механические исследования механизма деформации углеродных нанотрубок // Механика композиционных материалов и конструкций. 2009. Т. 15. № 3. С. 345–368.

18. Galimov N.K., Yakupov N.M., Yakupov S.N. Experimental-Theoretical Method for Determining Mechanical Characteristics of Spherical Films and Membranes of Complex Structure. *Mechanics of Solids.* 2011;3:380–386. https://doi.org/10.3103/S0025654411030058

19. Taplin J. (ed.) *Fracture mechanics. The destruction of the materials.* Congressional reports, Waterloo. Canada, June 19–24, 1977. Moscow: Mir Publ.; 1979. (In Russ.)

Таплин Д. (ред.) Механика разрушения. Разрушение материалов. М.: Изд-во Мир. 1979. 239 с.

20. Yakupov S.N., Gubaidullin R.I. Rigidity, adhesion and delamination of the coating in the “substrate — coating” system. *Structural Mechanics of Engineering Constructions and Buildings*. 2022;18(3):204–214. (In Russ.) http://doi.org/10.22363/1815-5235-2022-18-3-204-214

Якупов С.Н., Губайдуллин Р.И. Жесткость, адгезия и расслоение покрытия в системе «подложка-покрытие» // Строительная механика инженерных конструкций и сооружений. 2022. Т. 18. № 3. С. 204–214. http://doi.org/10.22363/1815-5235-2022-18-3-204-214

21. Yakupov S.N., Kiyamov H.G., Yakupov N.M. Mukhamedova I.Z. A new variant of the fem for evaluation the strenght of structures of complex geometry with heterogeneous material structure. *Case Studies in Construction Materials.* 2023;19:e02360. https://doi.org/10.1016/j.cscm.2023.e02360

22. Yakupov S.N., Kiyamov H.G., Yakupov N.M. Modeling a synthesized element of complex geometry based upon three-dimensional and two-dimensional finite elements. *Lobachevskii Journal of Mathematics.* 2021;42(9):2263–2271. https://doi.org/10.1134/S1995080221090316