AVALIAÇÃO DA DURABILIDADE DOS REVESTIMENTOS EM DIFÍCEIS CONDIÇÕES DE ESTRESSE

ASSESSMENT OF DURABILITY OF COATINGS IN DIFFICULT STRESS CONDITIONS

ОЦЕНКА ПРОЧНОСТИ ПОКРЫТИЙ В УСЛОВИЯХ СЛОЖНОГО НАПРЯЖЕННОГО СОСТОЯНИЯ

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RESUMO

Foram estudadas as propriedades mecânicas de revestimentos protetores à base de epóxi-poliéster aplicados a substratos de aço. Foram determinadas as características mecânicas dos revestimentos, bem como sua influência no comportamento das amostras sob carga mecânica. Testes de amostras com revestimentos, criados por métodos de nanoindentação, com posterior processamento de dados experimentais usando modelos analíticos simplificados padrão e usando modelagem numérica de elementos finitos, foram realizados. Em ensaios de tração, foi demonstrado que a presença de revestimentos leva a alterações na natureza da fratura das amostras. Nos testes de estabilidade, os resultados dos dados experimentais foram comparados com os resultados dos cálculos analíticos e numéricos, que demonstraram o efeito dos revestimentos na estabilidade de amostras de paredes finas. As propriedades mecânicas das amostras com revestimentos em um ou nos dois lados da amostra foram estudadas, o que também confirmou o módulo elástico dos revestimentos estudados em um nível de até 10 GPa (com o valor médio para materiais a granel até 3,5 GPa). No processo de teste em temperatura elevada, foi estabelecida a importância de garantir um aperto constrito das amostras na ausência dos quais ocorre um aumento significativo no erro de medição. Devido a deformações de temperatura, a rigidez das amostras é reduzida e, consequentemente, diverge das condições do selo rígido adotado nos cálculos. Os resultados obtidos visam desenvolver ideias sobre propriedades mecânicas bem como métodos para alterar e calcular propriedades mecânicas, revestimentos de proteção finos usados em várias indústrias e, em particular, uma ampla classe de revestimentos usados para proteger elementos estruturais das estruturas de aeronaves contra a corrosão.

Palavras-chave: *resistência do revestimento, tensões residuais, revestimentos protetores, modelagem de elementos finitos, módulo de elasticidade.*

ABSTRACT

The mechanical properties of protective powder coatings based on epoxy-polyester applied to steel substrates were studied. The mechanical characteristics of coatings, as well as their influence on the behavior of samples under mechanical loading, were determined. Tests of samples with coatings, created by Nano indentation methods, with subsequent processing of experimental data using standard analytical simplified models and using numerical finite element modeling were performed. In tensile tests it was demonstrated that presence of coatings leads to changes in the nature of fracture of the samples. In stability tests, the results of experimental data were compared with the results of analytical and numerical calculations, which demonstrated the effect of coatings on the stability of thin-walled samples. The mechanical properties of samples with coatings on one or both sides of the sample were studied, which also confirmed the elastic modulus of the studied coatings at a level of up to 10 GPa (with the average value for bulk materials up to 3.5 GPa). In the process of testing at elevated temperature, the importance of ensuring tight clamping of the samples was established, in the absence of which significant increase in the measurement error takes place. Due to temperature deformations, stiffness of the samples is reduced and, accordingly, deviate from conditions of hard seal

assumed in calculations. The results obtained are aimed at developing an understanding about mechanical properties, as well as about methods for changing and calculating mechanical properties, thin protective coatings used in various industries and, in particular, a wide class of coatings used to protect aircraft structural components from corrosion.

Keywords: *coating rigidity, residual stresses, protective coatings, finite element modeling, elastic modulus.*

АННОТАЦИЯ

Исследуются механические свойства защитных порошковых покрытий на эпоксидно-полиэфирной основе, нанесенных на стальные подложки. Определены механические характеристики самих покрытий, а так же их влияние на поведение образцов при механическом нагружении. Проведены испытания образцов с покрытиями методами наноиндентирования с последующей обработкой экспериментальных данных с использованием стандартных аналитических упрощенных моделей, так и с использованием численного конечно-элементного моделирования. В испытаниях на растяжение показано, что наличие покрытий приводит к изменению характера разрушения образцов. В испытаниях на устойчивость проведено сопоставление результатов экспериментальных данных и результатов аналитических и численных расчетов, которые показали влияние наличия покрытий на устойчивость тонкостенных образцов. Исследованы механические свойства образцов с покрытиями, нанесенными с одной или с двух сторон образца, которые также подтверждают значения модуля упругости исследуемых покрытий на уровне до 10 ГПа (при обычном значении для объемных материалов до 3.5 ГПа). В процессе проведения испытаний при повышенной температуре установлена важность обеспечения плотного зажима образцов, в отсутствие которого, происходит значительное увеличение погрешности проводимых измерений – вследствие температурных деформаций жесткость закрепления образцов снижается и, соответственно, отклоняются от условий жесткой заделки, принимаемой в расчетах. Полученные результаты направлены на развитие представлений о механических свойствах, а также о способах измерения и расчета механических свойств, тонких защитных покрытий, применяемых в различных отраслях промышленности и, в частности, широкого класса покрытий, применяемых для защиты от коррозии элементов конструкций авиационной техники.

Keywords: *прочность покрытий, остаточные напряжения, защитные покрытия, конечно-элементное моделирование, модуль упругости.*

1. INTRODUCTION

Polymer coatings are widely used in various fields of technology to protect structural elements from corrosion, and to provide electrical insulation, to control the frictional characteristics of surfaces, for decorative purposes, etc. (Gavrilova *et al.*, 2009) Getting reliable identification of mechanical properties of coatings is an important task from the point of view of ensuring their durability and wear resistance during operation (Gavrilova *et al.*, 2009; Gavrilov *et al.*, 2009). In the present dissertation, we provide the determination of the mechanical properties of coatings based on epoxy-polyester that are used to protect the structural elements of aircraft from corrosion. Based on the sequence of experimental studies and theoretical calculations, the elastic modulus of coating material is determined, the residual stresses acting in it, resulting from use of heat treatment during coating process (Zezin *et al.*, 2012a; Zezin *et al.*, 2012b; Gavrilov *et al.*, 2012).

The results can be used to assess the strength and durability of coating materials, and

to assess their impact on the mechanical behavior of protected thin-walled structures. When doing strength calculations of large-sized structures, the influence of coatings can be neglected if the wall thickness of the products significantly exceeds the thickness of the coatings and stiffness of coatings is much lower than stiffness of material of the structure. Nonetheless, if the thickness of the coating is comparable with the thickness of the structural element and if the coatings have sufficient rigidity, then their influence cannot be neglected in certain loading cases. From the point of view of strength calculations, thin-walled metal structural elements with polymer coatings can be represented in the form of two- or three-layer plates (depending on whether the coating is applied on one or both sides) with stiffer middle layer of metal and much more pliable outer layers -coatings. Now, not many experimental and theoretical works are known in which macroscopic mechanical behavior of such structural elements of this kind is analyzed taking into account the effects of the influence of residual stresses. We can note a wide variety of works in the field of study of functional gradient

thin-walled structures with coatings. However, in these structures it is usually assumed that the stiffness of the surface layers is higher compared to the inner area. Such structures are, for example, metal products with ceramic coatings or with hardened surface areas. The study of thin-walled structures with rigid middle layer and pliable thin outer layers has not received much attention. In linear problems of statics, experiments show that the influence of thin coatings can be neglected. Nonetheless, in more specific problems, for example, under conditions of finite strains, nonlinear elasticity, stability and vibration loading problems of thin-walled structures with coatings, neglect of influence of coatings can lead to calculation errors. Therefore, in this work, we study the intrinsic properties of mechanical coatings, evaluate residual stresses acting in them and their strength, and analyze the effect of coatings on the mechanical behavior of thin steel plates under static loading.

2. MATERIALS AND METHODS

Let us evaluate the strength of the coating in conditions of separation tests of cantilever-fixed sample. In order to do this, we consider the option of testing samples in the form of thin metal plates (strips) with coatings fixed at one end to a rigid substrate (Figure 1). Fixing to the substrate is realized by high-strength adhesive joints, the cohesive and adhesive strength of which exceeds the adhesive strength of the coating to the substrate and, accordingly, provides the possibility of changing the latter in this experiment. The plate is loaded by force at free end directed vertically upwards, while the rigid substrate is fixed on lower surface. So, the separation of the plate from the substrate is ensured. By high-strength adhesive, as it was said, the fracture is localized at the boundary of the coating with the substrate and, thus, in tests, it is possible to determine the maximum load at which this destruction begins. The destruction mechanism is complex in this case since both normal and shear stresses act in the presented test scheme in the coating and in the substrate. The maximum of these stresses is located at the point where the rigid substrate ends ($x = L - a$). We are performing calculations to estimate these stresses. In the calculations, we assume that the thickness of coating h_c and the adhesive joint h_a can be neglected and the problem of deformations of beam of thickness h fixed at one end on a steel substrate of thickness H can be considered. The shear force and bending moment arising in the beam determine the level

of stress at the boundary of its contact with a substrate and, accordingly, the desired stress level in coating.

The length of the cantilever beam extending beyond the rigid skid is a . Thus, the moment and shear force acting at the separation point are (Equation 1).

In the fixation area $x < L_a$ the beam deflections and its curvature remains zero, and, therefore, in the framework of classical beam theory, in this area in the beam, both moment and shear forces are equal to zero. Therefore, from the point of view of classical theory, the beam stays in unstressed state in fastening zone, and only at the boundary of the fastening zone concentrates bending moment and cutting force applied to it. Therefore, the classical theory does not allow us to estimate the level of stresses acting in the area of contact between the beam and rigid substrate (Geodesic..., 2005).

More acceptable estimates for the problem under consideration can be obtained by considering the Timoshenko beam model. This model is an approximation of the real deformed state of the beam, which, generally speaking, must be described, taking into account the effects of compression (Feodosiev, 2013; Grigolyuk and Tolkachev, 1980). By resolving shear deformations in the beam, it is possible to evaluate how its stress-strain state changes in fastening area, where there is no deflection and the curvature remains zero (the shifts are acceptable: the lower surface of beam remains in full contact with rigid substrate, and the upper moves relative to the lower due to externally applied load transmitted from loose end of the beam).

In the case of small deflections, the beam curvature in the framework of Timoshenko model is determined by the following relation (Equation 2) (Grigolyuk and Tolkachev, 1980). Where $y(x)$ – is the deflection of the beam, M – is bending moment – is shearing force, E – is Young's modulus of beam material (metal sample, in this case), G – is shear modulus of the beam, $I = bh^{3/12}$ – is iteration moment in beam section, $F = bh$ cross-sectional area, $5/6$ – correction ratio introduced in the theory of Timoshenko (Timoshenko and Gere, 2002), the hatch denotes the derivative in the x direction (Beam Deflection..., 2019).

Given that in the fastening area, the beam curvature equals zero, and the cutting force is related to the moment (Equation 3), the differential equation for bending moment has the

form (Equation 4).

The boundary conditions for this equation are determined from (1) on the right end and on condition of absence of load on the left, that is, it is possible to use conditions of the form (Equation 5) or (Equation 6).

It is impossible to satisfy both conditions in terms of moment and shear force (4) since in the recorded model there are not enough constants for this. Fulfillment of this condition at the remote end of the fixed beam is mandatory since it implies the absence of angles of rotation of the beam sections, which is performed either in case of symmetry of problem under consideration or in case of sufficient length of the beam fixing area.

The general solution to problem (2) has this form (Equation 7).

Given the boundary conditions (4) and simplifications, we get the distribution of internal force factors and transverse load in the fastening area (Equation 8).

Let us note that shearing force in (6) determines the shear stresses that are realized in the beam and at the boundary of its contact with the substrate. The nature of the distribution of tangential stresses over the thickness of the beam outside the area is described by a parabolic dependence, however, in the contact area this dependence deviates from the classical law, primarily because the tangential stresses on the lower surface of the beam cease to be zero due to its conjugation with the substrate. By analogy with the classical approach, it is suggested to introduce the following estimate to determine desired tangential stresses at the contact of the beam with the substrate using the correction factor (Equation 9).

These stresses (9) lead to the cut of the coating from the substrate. Normal stresses that lead to separation of coating are estimated based on distributed nominal load (8). Value is linear load, respectively, normal stresses are determined by the following relationship, in which we also introduce a correction factor (Equation 10).

The ratio k_σ, k_τ are proposed to calculate by comparison of the obtained solutions with numerical modeling for the problem under consideration (see below). The maximum tangential and normal stresses that can be used in the processing of experimental data are realized at the boundary of the pinning area and have the form (taking into account the definition

for α in 3)) (Equation 11-12). Where ν – is the Poisson coefficient of the beam material.

From the obtained solutions (9) – (12), it can be seen that the stresses decay exponentially with distance from the boundary of the fastening area (in accordance with the Saint-Venant principle). The maximum values of these stresses depend on the parameters of the model. They are proportional to the applied load and length of loose end of the sample protruding beyond the substrate, and proportional to the width of the sample and the square of its thickness. With a sufficiently large extent of the fastening area ($L \gg a$), the tangential stresses practically cease to depend on its length, since the free end of the beam ceases to influence at the point $x = 0$ (Equation 13).

In this case, constant relationship between tangential and normal stresses is realized, which is determined by the Poisson's ratio of beam material (Equation 14).

In case of a small length of the fastening area, the effect of the end of the beam, at which the zero load is set ($x = 0$), is still insignificant. Figure 2 shows that with an increase in the relative length of the substrate (in fractions of the sample thickness), the level of maximum tangential stresses rapidly decreases and reaches an asymptotic value. Changing this level is realized within 5% of the asymptotic value for any value of the Poisson's ratio characteristic of structural materials.

As a result, for processing the experimental data, we can use the simplest relations (13), (14), in which it remains only to determine the correction coefficients. This was accomplished by comparing the results of calculations with numerical modeling. A two-dimensional model was considered within the framework of planar stress state hypothesis, presented in Figure 3. The model consists of a steel beam and a steel substrate, between which the conditions of ideal contact with respect to displacements and stresses are indicated. At the loose end of the beam, a load is applied, acting in the vertical direction and distributed at the end of the beam. The bottom surface of the base is fixed, or symmetry conditions are set on the left border of the beam (this condition corresponds to loading sample according to the three-point bending scheme, which is easy to implement in experiments using standard equipment).

In calculations, square elements of the second order (with quadratic approximation) are used. The material of the entire model is steel.

The coating on the beam and the adhesive bond layer are not shown under the assumption that their thickness is small.

We are considering models with different lengths and thicknesses of beams. The thickness of the beam always stays 3 elements. A small "skew" of 0.5 mm in size was made at the boundary of the beam fixing area, which ensures the independence of the solution from the mesh size (otherwise, a right angle and stress concentration arise). In the calculations, the load value was set as 5 N. The length of the entire model was 100 mm, the width was set equal to 10 mm.

3. RESULTS AND DISCUSSION:

To process the test results for samples with coatings, numerical, and analytical calculations were performed. The influence of residual stresses on identification results for Young's modulus of coatings was estimated. In the calculations, estimates for the values of residual stresses were used, both according to the classical relations (Stoney, Bollen), and according to the refined formulas that take into account deformations in the plane of sample and its deformation, for plates of small thickness.

A study was made of the effect of coatings on the mechanical behavior of samples under conditions of testing on tension and stability at normal and elevated temperatures. In tensile tests it was demonstrated that presence of coatings leads to changes in the nature of fracture of the samples. In stability tests, the results of experimental data were compared with the results of analytical and numerical calculations, which demonstrated the effect of coatings on the stability of thin-walled samples. In the process of testing at elevated temperature, the importance of ensuring tight clamping of the samples was established, in the absence of which significant increase in the measurement error takes place – due to temperature deformations, stiffness of the samples is reduced and, accordingly, deviate from conditions of hard seal assumed in calculations.

4. CONCLUSIONS:

A technique is proposed for assessing the strength of contact of coatings with the substrate under the action of normal and shear stresses in bending tests. As a result of experiments and simulations, strength estimates of coatings under consideration were obtained.

The obtained results can be used to assess the durability of protective coatings, to assess the optimality of some technological modes of their manufacture, and to predict the occurrence of technological defects and defects that arise during operation.

As a result of the conducted research, it is possible to perform tests for thermal conditions and thermal cycling in the future. The main theoretical provisions for doing these works are considered in (Formalev et al., 2015; Formalev et al., 2017; Babaytsev et al., 2017; Lomakin et al., 2017; Kakhramanov et al., 2017; Bulychev et al., 2018; Formalev et al., 2018; Kuznetsova et al., 2018; Lomakin et al., 2018; Nikitin et al., 2019; Rabinskiy et al., 2019; Rabinskiy and Tushavina, 2019a; Rabinskiy and Tushavina, 2019b; Formalev and Kolesnik, 2019).

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$$M(L-a) = Pa, \quad Q(L-a) = P \quad (\text{Eq. 1})$$

$$\frac{d^2 y(x)}{dx^2} = \frac{M(x)}{EI} - \frac{5}{6GF} \frac{dQ(x)}{dx} \quad (\text{Eq. 2})$$

$$Q(x) = \frac{dM(x)}{dx} \quad (\text{Eq. 3})$$

$$\underline{x < L-a}: \frac{d^2 M(x)}{dx^2} - \alpha^2 M(x) = 0 \quad \alpha^2 = \frac{5GF}{6EI} \quad (\text{Eq. 4})$$

$$\underline{x = L-a}: M(x) = Pa \quad \underline{x = 0}: M(x) = 0 \quad (\text{Eq. 5})$$

$$\underline{x=L-a}: \frac{dM(x)}{dx} = Q(x) = P \quad \underline{x=0}: M(x) = 0 \quad (\text{Eq. 6})$$

$$M(x) = C_1 e^{\alpha x} + C_2 e^{-\alpha x} \quad (\text{Eq. 7})$$

$$M(x) = Pa \frac{sh(\alpha x)}{sh(\alpha(L-a))}, Q(x) = \alpha Pa \frac{ch(\alpha x)}{sh(\alpha(L-a))}, \quad (\text{Eq. 8})$$

$$q(x) = \alpha^2 Pa \frac{sh(\alpha x)}{sh(\alpha(L-a))}$$

$$\tau_{xz} = k_\tau \frac{Q(x)}{bh} = k_\tau \frac{aP\alpha}{bh} \frac{ch(\alpha x)}{sh(\alpha(L-a))} \quad (\text{Eq. 9})$$

$$\sigma_z = k_\sigma \frac{q}{b} = k_\sigma \frac{aP\alpha^2}{bh} \frac{sh(\alpha x)}{sh(\alpha(L-a))} \quad (\text{Eq. 10})$$

$$\tau_{\max} = \tau_{xz}(L-a) = k_\tau \frac{aP}{bh} \sqrt{\frac{5GF}{6EI}} cth \left((L-a) \sqrt{\frac{5GF}{6EI}} \right) = \quad (\text{Eq. 11})$$

$$= k_\tau \frac{aP}{bh^2} \sqrt{\frac{5}{1+\nu}} cth \left(\frac{L-a}{h} \sqrt{\frac{5}{1+\nu}} \right)$$

$$\sigma_{\max} = \sigma_z(L-a) = k_\sigma \frac{aP}{b} \frac{5GF}{6EI} = k_\sigma \frac{Pa}{bh^2} \frac{5}{1+\nu} \quad (\text{Eq. 12})$$

$$t_{\max} \Big|_{L-a} = k_t \frac{aP}{bh^2} \sqrt{\frac{5}{1+n}} \quad (\text{Eq. 13})$$

$$\frac{t_{\max}}{s_{\max}} \Big|_{L-a} = \frac{k_t}{k_s} \sqrt{\frac{1+n}{5}} \quad (\text{Eq. 14})$$

Figure 1. Testing setup for coated samples cantilevered on a rigid substrate

Figure 2. Dependence of maximum tangential stresses at the separation point on dimensions of the sample fixing area. Colors: blue – $\nu = 0.2$, yellow – $\nu = 0.3$, green – $\nu = 0.4$

Figure 3. The finite element model of the beam fixed to the substrate, loaded according to the cantilever (top) and three-point (bottom) bending scheme