The quality analysis of the anti-corrosion coatings metal structures operating in difficult conditions

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Abstract. The simplest and most reliable way to protect metal structures from corrosion are the paint coatings, which, in comparison with other protection methods, have several advantages (manufacturability, maintainability, economy, compatibility with other protection methods, etc.). The issues of experimental quality analysis of the typical anticorrosion coatings designed to protect metal structures operating under aggressive environmental conditions and industrial factors are considered. It is proposed to use such indicators as adhesion, thickness and weather resistance as the main indicators of the coatings’ quality. The methods for the experimental determination of these parameters on the laboratory samples and the construction of an integral indicator of the anti-corrosion coatings quality are proposed. On the selected typical coatings example, the experimental dependences of their quality indicators on temperature, the number of “freezing-heating” cycles, the magnitude of the shock load and the water salinity degree are analyzed. The obtained data were used to determine the weather resistance of coatings and their quality indicator, which was proposed to use as the sufficiency integral indicator. Its essence lies in the assumption that there is a border beyond which an increase in the indicator is pointless for each of the quality indicators, since it does not lead to an improvement in the coating quality and can even be harmful due to the other uncontrolled indicators’ possible deterioration.

1. Introduction

Metal structures and materials used in various objects are exposed to strong corrosive effects of climatic and technogenic factors during operation. These factors include temperature, moisture, and mechanical stress [1-3]. Lowering the temperature and especially its sharp fluctuation lead to cracking and peeling of the coatings under the internal stresses influence arising from the difference in the coefficients of the film and the substrate thermal expansion. Under the influence of moisture, the paint coating swells, softens, and the water-soluble impurities are washed out of it. In addition, water accelerates the process of the binders’ degradation [4]. Water salinity has the greatest effect on the protective properties of coatings.

Therefore, an important place in the problems of ensuring the efficiency and safety of the metal structures’ operation is occupied by the search for the most rational ways to protect them from corrosion [5-8]. It is quite natural that when choosing the anticorrosive coatings, one should be guided by the operating conditions corresponding to the maximum environment aggressiveness.

2. Methods and Materials
Modern anticorrosive coatings used to protect metal structures are currently a system of dissimilar materials applied to the surface to be protected in a certain sequence. The first layer of this material system is called priming, and the material used is called a primer. Under the term “primer” two concepts are identified: the paintwork material itself, used for applying to the surface and the coating film formed from this material. The main purpose of the primer is to ensure good adhesion between coatings. The primer also performs protective functions on the metal surfaces, exerting a significant influence on the electrochemical and diffusion processes occurring at the metal - coating interface.

The primer’s properties are thus determined by its chemical composition: the film former nature, the type of pigments and fillers, the nature of the special additives used. On the other hand, the primers’ properties largely depend on the nature of the surfaces to be painted and the quality of these surfaces’ preparation before coating.

The following layers of the metal structures protective coatings include anticorrosion and coating enamels. Such coatings have a sufficiently high weather resistance and do not erode when exposed to the salt water flows on the metal structure.

As typical samples of such coatings, we will choose anticorrosive primers and enamels that are widely used to protect the metal structures, which are exposed to aggressive environmental influences, including salt water. These include primers FL-03k, EF-065, VL-02 and VL-023, enamels MS-17, XC-5226 and EP-46U.

It should be noted that thixotropic paints and varnishes applied by the airless spraying machines are currently being developed and used. Such paints and primers, due to the changing viscosity during single-layer application, make it possible to obtain the coatings with a thickness of 80-200 microns. The primers of this type can simultaneously serve as an anticorrosive coating. As a typical sample of such a material, we consider the “Tectyl BT Coat” primer, which is a thixotropic anticorrosive composition based on mineral oil, intended for processing the metal structures for various purposes exposed to fresh and sea water. When applied, it forms a thick, oily, translucent film with a recommended thickness of 80 microns and a coating 12,5 m²/l.

To conduct a comparative analysis of these anticorrosive materials, a series of laboratory experimental studies to determine their main physical and mechanical properties: adhesion, thickness, and weather resistance was carried out.

Coating adhesion, i.e. the adhesion force between the protected surface (substrate) and the anticorrosive material was determined based on the lattice notching and tearing methods. The coating adhesion was determined by the tear strength value \( \sigma = F/A \), where \( F \) – is the adhesive tape peeling force, N; \( A \) is the area of the torn fragments of the coating, mm².

The dry coating thickness on steel samples was monitored using a MikroTest magnetic thickness gauge.

Weather resistance, i.e. the ability of the coating to maintain its physical and mechanical characteristics after exposure to various climatic factors was determined by the dependence of the selected characteristics on temperature, the number of temperature drops, energy of shock loads and salinity of sea water.

For the experiment, the samples, which are plates with a size of 150x100mm and a thickness of 5mm from the materials St45 and aluminum alloy D16T were made. The studied anticorrosion coatings were applied to the samples using the “Fakel-4” airless spraying unit. After a certain time required for the dry coating film formation on the sample’s surface, its basic physical and mechanical properties were checked under normal conditions (temperature 22°C and relative humidity 60%). Then the samples were subjected to several types of influences: low and high temperatures and a given number of transitions (drops) in temperature through a zero value in the Nema climate-heat chamber; impact on a pendulum-type machine; vibration loads on a vibrating stand; the sea water salinity influence. Each anti-corrosion coating was carried out independently of the others. After each type of exposure, the physical and mechanical parameters of the coating were checked, and their change was evaluated in relation to the indicators obtained under normal conditions.
3. Results and discussions

Initially, the temperature effect was investigated. The coating material was tested to determine the basic physical and mechanical characteristics when the temperature changes from $-10^\circ$C till $50^\circ$C in increments of $5^\circ$C. The samples with the studied coating were placed in a Nema climate chamber and kept for 20 minutes, which is sufficient for complete the coating layer cooling or heating. Based on the obtained experimental data, the graphs of the corrosion-resistant coatings main physical and mechanical characteristics (adhesion $\sigma$, thickness $H$) dependence on temperature are plotted, shown in Figure 1. At the same time, the data for the studied ordinary primers and enamels were averaged.

An analysis of the data obtained shows that the adhesion value of the Tectyl BT Coat anticorrosion coating at normal temperature is slightly lower than that of the conventional hard coatings, and when the temperature is lowered to $-10^\circ$C even increases slightly, because The Tectyl BT Coat forming the oily film hardens, enhancing adhesive strength with the substrate. With increasing temperature to $+40^\circ$C adhesion value decreases slightly by 1-5% according to the linear law, and then drops sharply due to the coating “melting”, which turns into a viscous liquid.

The conventional hard primers exhibit instability in behavior when temperature changes. Although under normal conditions the adhesion is greater than that of Tectyl BT Coat, but with an increase or decrease in temperature, it sharply decreases, which leads to cracking and peeling of the coatings under the internal stresses’ influence arising from the difference in the film and the substrate thermal expansion coefficients. Enamels adhesion practically does not change.

The thickness of the Tectyl BT Coat coating remains at about 80 $\mu$m with the temperature changes, and at $+40^\circ$C the thickness decreases sharply - by 50%, in connection with the oily coating spreading. But even so, its thickness remains greater than that of conventional hard primers, the thickness of which, under the same conditions, decreases due to the binders’ evaporation. Enamel thickness for the same reasons decreases by almost 40%.

The Tectyl BT Coat flexibility at normal temperature is two times higher than that of hard coatings due to the presence of viscous binders. The limiting value of the sample’s bending is most strongly affected by a decrease in temperature. With Tectyl BT Coat, flexibility is reduced by 50%, and with conventional hard coatings by 60%. But even at low temperatures, Tectyl BT Coat’s flexibility remains higher than that of the conventional coatings at normal temperature.

Next, the effect of the number of “freeze-heat” cycles for conventional and thixotropic primers was investigated. Experimental dependences of the anticorrosion primers’ basic physical and mechanical characteristics on the number of cycles $n$ Figure 2. One cycle was cooling from normal temperature to $-10^\circ$C, subsequent increase to $50^\circ$C and return to normal temperature. Thus, the temperature transition through a zero value was simulated during the operation of the metal structure. The initial number of cycles for each of the coatings was 10, the increment of 5 cycles. The maximum number of cycles in the experiment was 70, which corresponds to the average number of days per year with the temperature drops during the metal structure operation in a temperate cold climate region.

![Figure 1](image1.png)

**Figure 1.** Dependence of coating characteristics on the temperature:
The data obtained show that the adhesion value of the conventional hard coatings with an increase in the number of temperature transitions through zero to 70 decreases by 4 times, while that of the Tectyl BT Coat decreases by 5-10%. “Tectyl BT Coat” coating thickness decreases by 5% with an increase in the number of cycles; in the conventional hard coatings, it is halved.

![Graph showing the dependence of characteristics of primers on number of cycles](image)

**Figure 2.** The dependence of the characteristics of the primers on the number of “Freezing-heating” cycles

The bending value of both hard coatings and Tectyl BT Coat decreases by half with an increase in the number of cycles.

To study the impact strength of the coatings, the samples were fixed in the installation in such a way that the impact of the pendulum hammer hit the rear side of the sample. The magnitude of the impact E kinetic energy varied in the range from 1 to 6 J with a step of 1 J. The experimental dependences of the coatings’ physical and mechanical characteristics on the impact energy are presented in Figure 3.

After the impact, peeling and cracking of ordinary hard anticorrosion coatings with the impact energies of more than 3 J were observed. The decrease in adhesion of the Tectyl BT Coat coating is more uniform and its value decreased by half at an impact energy of 6 J, while in hard coatings a decrease of more than four times was observed. The coatings thickness practically does not depend on the impact energy. The number of microcracks in conventional coatings with an increase in impact energy increases exponentially by more than two times, which is explained by cracking and chipping of the material. For Tectyl BT Coat, the S value increases linearly.

The sea water salinity has the greatest impact on the protective properties of coatings that are constantly in sea water or periodically in contact with it. First of all, this applies to the coatings of the metal structures’ underwater part, as well as the tanks for various purposes, periodically filled with water. The sea water salinity can reach 40%, and with an increase in the salt content, the electrical conductivity and, consequently, the sea water aggressiveness increase.

In this regard, the samples with a corrosion-resistant coating were placed in containers, each of which was filled with water with various salinity degrees. The water salinity ranged from 0 to 50% with an increase of 10% in each tank.
The samples were kept in water for 10 days, and then the coating material was tested to determine the basic physical and mechanical characteristics. The results of experimental studies of the dependence of the physical and mechanical coatings’ characteristics on the percentage of salts in water are presented in Figure 4.

The decrease in the coating adhesion under the influence of salt water occurs smoothly and reaches the following values at a concentration of 45%: for the ordinary hard coatings - a decrease of four times, for Tectyl BT Coat - of two times. Under the salt water influence, all coatings soften and water-soluble impurities are washed out of them, which leads to a decrease in the coating thickness. As a result of the experimental studies on the study and analysis of the basic physical and mechanical properties of traditional and thixotropic anticorrosion coatings used to protect the metal structures, it was found that under different operating conditions, various materials have both advantages over others and disadvantages. Therefore, to make a reasonable choice of the preferred option for the metal structures’ anticorrosion treatment, it is proposed to use the approaches proposed in [9–15] for multicriteria selection (ranking) of the technical objects using the concept of sufficiency introduced there. In accordance with the introduced concept of sufficiency in [9] and the criterion [10] that implements it, the composition of anticorrosion treatment having the maximum value of the sufficiency index is recognized as “the best”.

In this case, the integral deviation degree of the particular indicators from the requirements (sufficiency levels) will be minimal, thereby ensuring the maximum protection quality of the vehicle body structure from the corrosive effects of different physical nature factors.

The main difficulty in obtaining the sufficiency criterion for evaluating the anticorrosive compositions is to determine the weight coefficients that establish the preference of some criteria over others. Using the functional method for determining the weight coefficients, we will evaluate the
sufficiency of the proposed anti-corrosion treatment compositions of the vehicle. To do this, we determine the values of the most important indicators $y_j$, characterizing the anti-corrosion coating parameters, the sufficiency levels $y_{ti}$, and tolerances from them $y_0j/y_{Mj}$ ($y_0j$, $y_{Mj}$ - the minimum and maximum indicator values at which the anti-corrosion coating use is possible), as well as the non-linearity indicator $n_j$ characteristic functions, which are given in Table 1.

### Table 1. Modeling indicators

| The indicator characterizing the automatic transmission parameters | ACP Property      | The minimum value of the indicator $y_0j$ | The maximum value of the indicator $y_{Mj}$ | Adequate indicator value $y_{tj}$ | Units |
|---------------------------------------------------------------|-------------------|---------------------------------------|-------------------------------------|--------------------------------|-------|
| $y_1$, $\sigma$ adhesion                                      |                   | 10$^{-2}$                              | 2                                   | 0.3                            | MPa   |
| $y_2$, $H$ thickness                                          |                   | 1                                     | 100                                 | 30                             | μm    |
| $Y_3$ weather resistance                                      |                   | 0.03                                  | 3                                   | 1.0                            | year  |

All the considered anti-corrosion materials were evaluated by the modeling indicators characterizing the surface quality in terms of the assessing adhesion, thickness and weather resistance of the coating. The sufficiency indicator values obtained from the results of calculations $z_i$ rank the compared anti-corrosion compounds in the order shown in Table 2.

### Table 2. Corrosion-resistant coatings

| Nº p/p | ACP name                  | Sufficiency indicator value $z_i$ | Ranking place |
|--------|---------------------------|----------------------------------|----------------|
| 1.     | Primer FL-03k             | 0.88                             | 4-5            |
| 2.     | Primer EF-065             | 0.85                             | 7              |
| 3.     | Primers VL-02 and VL-023  | 0.91                             | 2              |
| 4.     | Primer MS-17              | 0.88                             | 4-5            |
| 5.     | Enamel EP-46U             | 0.87                             | 6              |
| 6.     | Enamels HS-5226           | 0.9                               | 3              |
| 7.     | Primer "Tectyl BT Coat"   | 0.92                             | 1              |

4. **Summary**

Thus, it can be concluded that the best of the compared anti-corrosion coatings for the metal structures operating in difficult conditions is the Tectyl BT Coat thixotropic primer, although the traditional coatings from the point of view of the introduced sufficiency indicators satisfy the requirements of 85-90%. The considered experimental research methodology and the subsequent integral sufficiency assessment of meeting the requirements is universal and represents a tool that can be used to solve the problems of multi-criteria selection or ranking of a finite number of different anti-corrosion coatings or other objects.

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