The Application of Statistical Methods in Assessing the Quality of Finishing of Building Products and Construction

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Abstract:

Information is provided on the application of statistical methods for managing the quality of products when painting building products and structures. It is shown, that the quality of the finish depends on the method of applying the paint, the porosity of the cement substrate. For coatings based on all types of paints the minimum roughness value of the coating surface and the minimum value of the risk are typical in the case of applying paints to the putty surface, regardless of the method of application. Offered to organizations, firms, engaged in the execution of finishing works, the introduction of the kaizen approach to the renewal of staining technology, based on continuous improvement of activities and providing for the use of statistical methods for managing the quality of products. Information on the effect on the longevity of coatings of the quality of their appearance is given. It is shown, that coatings with a high roughness index are characterized by low durability during exploitation. A model of the cohesive strength of coatings is presented, depending on the surface roughness.

Keywords:

Statistical Methods, Risk, Coefficient of Variation, Quality of Finish, Roughness

1. Introduction

One of the main conditions for the supplier to enter the market with competitive products (service) is its quality. The basis for providing and improving the quality of products under production conditions is the effective use of information on the quality of the flow of technological processes. Accurate compliance with technology requirements is a guarantee of product quality, however, the implementation of the key principle of modern quality systems - "continuous improvement" requires constant analysis of the current situation and making adjustments to technological processes. An analysis of the developments of foreign authors shows that effective introduction of statistical control methods allows to sharply reduce the percentage of rejects, increase labor productivity, continuously and timely identify and eliminate production shortcomings [1-4].

The use of statistical tools helps to find out where, when, by whom, under what conditions some interference in the process is caused. With the help of these methods, you can specify where to improve the quality of the product, its design or manufacturing technology must be changed. Statistical methods are allowed to regulate the technological process in such a way that production marriages are minimized.

Practice shows that effective introduction of statistical control methods allows to sharply reduce the percentage of rejects, increase labor productivity, continuously and timely identify and eliminate production deficiencies.

In work [5] three problems in Taguchi's on-line quality feedback control system are discussed. Furthermore, countermeasures for improving the system are proposed. First, the quality loss of products that are out of control is reestimated by approximating the probability density of their quality characteristic value to a linear distribution. Second, the quality loss of products that are under control is reestimated by approximating the probability density of their quality characteristic value to a normal distribution. Third, the decreased profit resulting from a process shutdown, which is excluded in Taguchi's on-line quality feedback control system, is considered in calculating the adjustment cost. The management cost and quality loss constitute the total quality cost. In the improved on-line quality feedback control system, the optimal measurement interval and optimal administrative boundary are calculated by minimizing the total quality cost using an iterative method.

We conducted an analysis of the risks related to the first group (risks of defects) during the finishing works. In a competitive environment important role of paintwork materials, aimed at creating high-quality coatings with good protective and decorative properties. Building and maintaining the working condition of buildings and structures require a large number of paint and varnish compositions. Growing competition in the market of finishing materials, increasing demands of consumers require manufacturers to obtain high-quality painted surfaces. The problem of safety of paint and varnish coating properties during storage and operation is significant and relevant. On coating can act a whole complex of factors, leading to a decrease in protective and decorative properties? These include: sunlight, high and low temperature, surface contamination, high humidity, development of mold, mechanical influences leading to the destruction of the coating, reducing its adhesion to the substrate, changing the color and gloss of the coating.

In accordance with the statistical theory of the strength of solids, the probability of destruction of coatings is determined by the presence and concentration of defects, including on the surface of the coatings. Consequently, the quality of the appearance of protective and decorative coatings determines their stress state and resistance in the process of exploitation

Durability of protective and decorative coatings of building products and structures averages 5-6 years. As practice shows, the destruction of coatings begins after 2-3 years of operation. Surveys were carried out on the state of the painted surface of the facades of buildings in Penza, st. Tsiolkovsky (Figure 1), st. Kalinin (Figure 2).

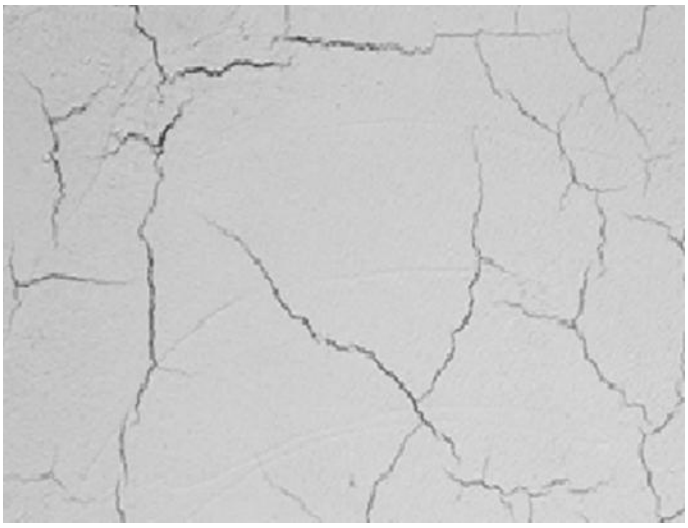

Figure 1. *Photo of the facade of the building along Tsiolkovsky Street after three years of operation, Penza (paint PF-115)*

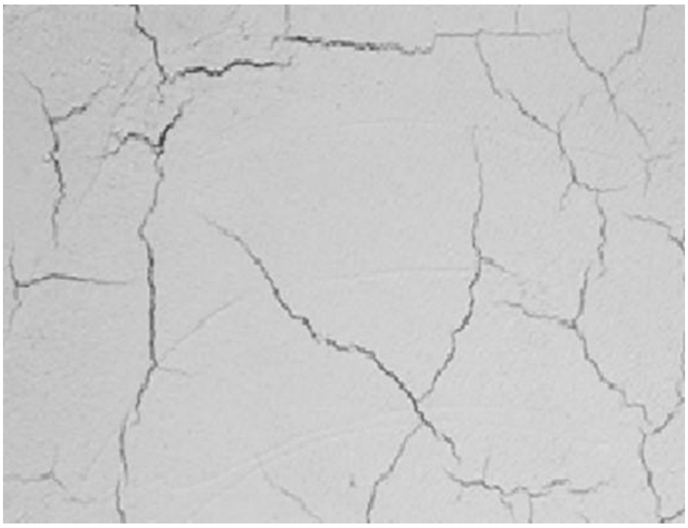

Figure 2. *Photo of the facade of the building along Kalinina Street after three years of operation, Penza (paint VD-AK-111)*

It is known, that the durability of paint and varnish coatings is determined by the quality of their appearance, and depends on the rheological properties of the paint composition, the technology of preparation of the surface before painting, the method of application, etc. [6, 7, 8]. The correlation dependence between the scatter of quality indicators of the painted surface and the financial losses that can be expected due to this is established in [9]. From this it should be noted that the operating costs for the repair of painted surfaces can be reduced due to a higher production culture, which provides for a reduction in the standard deviation

Below is an example of the application of statistical methods. Below is an example of calculating the risk of a "human factor", i.e. related to the quality of labor of personnel. The greater the value of the standard deviation, the higher the uncertainty of the appearance of a particular parameter value and, consequently, the higher the risk associated with the fact that the necessary (necessary) value of the parameter will not be obtained.

2. Mechanical Faults and Fault Signature

2.1 Materials and Methods

Coatings were made available with different roughness. After complete curing of the coating of these samples was cut blade size 5, 0 x 1, 0 cm, the thickness of each sample was measured with a micrometer.

Samples of the films were tested for tensile testing machine brand IR 50-57 to set the speed of the traverse of 87.5 m / s. The coating stress strain properties estimation was carried out with the help of a tensile machine IR 5057-50 with the samples after 28 days of air and dry curing. The method is based on the sample stretching until it ruptures at a deformation speed of 1mm/min. The 1x1x5 cm samples were fixed in the clips of the tensile machine so that their longitudinal axis was in the direction of stretching, and the force was applied equally all over the sample section. The tests were carried out at the temperature of 20 ° C and relative air humidity of 60%. The ultimate tensile strength estimation was carried out for not less than four samples of each compound. The ultimate tensile strength R_{kog} for each sample was calculated by formula

$$R_{\text{kog}} = \frac{F_{Pi}}{S_{0i}} \quad (1)$$

where F_{Pi} - the stretching loading at the time of a rupture, N;

S_{Oi} - the initial cross-sectional area of a sample, mm^2.

The modulus of elasticity for each sample (E_{upr}) in MPa was calculated by formula:

$$E_{upr} = \frac{R'_{kogi}}{\varepsilon'_i} \cdot 100 \quad (2)$$

where R'_{kogi} – the ultimate tensile strength at the time of the tangent separation from the chart "tension-deformation", MPa;

ε'_i – relative lengthening at the time of rupture, %.

The following paints were used: alkyd grade enamel PF-115, oil paint MA-15, acrylic water-dispersion paint (facade). The paints were applied with a brush, pouring, airless method on substrate in two layers with intermediate drying for 20 minutes. Samples with volume porosity of 24%, 28%, 32% were used in the work. Part of the surface of the samples before applying the paint composition was putty. The quality of the appearance of the coatings was assessed by the surface roughness. Roughness was determined with the help of the TR-100 profilograph device. A total of 50 measurements were taken on each surface.

To compare different solutions with different expected result and different risks, the coefficient of variation was used:

$$\gamma = \frac{\sigma}{\Pi_{cp}} \quad (3)$$

The value of the coefficient of variation characterizes the size of the risk per unit of the expected result. Therefore, the variant having the smallest value of and should be chosen as the least risky (with a lower relative risk).

The weighted-average value of the analyzed parameter $П_{cp}$, (the causal risk factor), was determined by the formula:

$$П_{cp} = \sum П_i * P_i \quad (4)$$

Where $Пi$ - the *i-th* value of the parameter being analyzed;

Pi - probability of occurrence of the *i-th* value of this parameter.

The variance of the values of the analyzed parameter was calculated by the formula

$$D = \sum \left(П_i - П_{cp}\right)^2 * P_i \quad (5)$$

The coefficient of variation was determined by the formula

$$\upsilon = \frac{\sigma}{\bar{x}} \quad (6)$$

where ρ the standard deviation;

S - average value of indicators.

3. Results and Discussion

The results of the studies are given in Tables 1-2.

***Table 1**. The quality of the appearance of the coatings in dependence from the method of its application and the porosity of the substrate*

Type of the paint	Roughness, R_a, mkm											
	Method for applying a paint composition											
	Brush				pour				Airless method			
	Porosity of the substrate, %				Porosity of the substrate, %				Porosity of the substrate, %			
	0	24	28	32	0	24	28	32	0	24	28	32
alkyd grade enamel PF-115	1,28	3,14	1,79	4,34	1,06	2,97	2,99	4,32	2,60	6,37	7,65	6,98
oil paint MA-15	1,79	3,13	4,27	5,65	2,26	5,60	4,05	3,07	2,85	4,37	4,53	5,41
acrylic water-dispersion paint (facade).	2,58	6,52	4,80	3,56	3,40	5,54	3,70	4,25	-	-	-	-

Analysis of the data (Table 1-2) indicates that the value of the surface roughness of the coating depends on the method of applying the paint composition, the porosity of the cement substrate. Thus, for coatings based on all types of paint compositions, the minimum value of the surface roughness of coatings is characteristic in the case of applying paints onto the putty surface, regardless of the method of application thereof.

When painting the surface with PF-115 paint, the minimum risk value is observed, when the paint is applied airless method to the substrates with a porosity of 28-32 %. The value of the coefficient of variation is 17-25%, respectively. When coloring with a brush, the risk values are maximum.

When oil paint MA-15 (green color) is applied airless method, is observed a lower degree of uncertainty, and hence the minimum value of the risk is observed with the porosity of the substrate 24% and on the putty surface. When applying paint with a brush the minimum value of the risk is observed with porosity of the substrate 28-32%.

The presence of defects on the surface coating will no doubt have an impact on the physical and mechanical properties of coatings. At the same surface area S coatings the probability of failure increases with increasing the concentration of defects. Regardless of the type of the paint are observed decrease of strength and relative deformations with increasing roughness of the coating surface [9, 10, 11, 12].

Table 2. *Statistical indicators of surface quality of paint coatings*

Type of the paint	**Weighted average roughness value, mkm**											
	Method for applying a paint composition											
	Brush				**pour**				**Airless method**			
	Porosity of the substrate, %				**Porosity of the substrate, %**				**Porosity of the substrate, %**			
	0	24	28	32	0	24	28	32	0	24	28	32
alkyd grade enamel PF-115	1,28 0,35	3,14 0,42	1,79 0,40	4,34 0,49	1,05 0,48	2,97 0,51	2,99 0,43	4,32 0,39	2,60 0,36	6,37 0,30	7,65 0,17	6,98 0,25
oil paint MA-15	1,79 0,38	3,13 0,53	4,27 0,30	5,65 0,32	2,25 0,46	5,60 0,33	4,04 0,38	3,07 0,47	2,84 0,29	4,37 0,30	4,53 0,37	5,40 0,46
acrylic water-dispersion paint (facade	2,58 0,39	6,52 0,39	4,80 0,40	3,55 0,36	3,40 0,48	5,54 0,38	3,70 0,45	4,25 0,42	-	-	-	-

Note. Above the line are numerical values of the average weighted surface roughness indicators of the coatings, and below the bar - the values of the coefficients of variation

When the surface is painted with water dispersion paint, the values of the variation indices practically do not differ from each other.

A decrease in the coefficient of variation indicates a decrease in the standard deviation. The more standard deviation σ of the process fits in the tolerance field, the fewer defects will be produced in production. The results of the investigations are correlated with the data [13]. The authors used the holography method for assessing the quality of coatings a non-destructive testing. The key point of the holographic non-destructive testing is that the fault isolation is determined by the pattern abnormality of the interference fringes [14, 15]. Interferograms are typically obtained by double exposure team by comparing two states of the sample surface before and after the impact or loading. The internal paint defects are detected by the pattern of fringes if they cause enough disturbance of the displacement field, and thus of the interference pattern observed on the sample surface.

When analysing the interferogram we can see, that the greatest distortion of the interference fringe pattern is observed on the coating on the cement backerboard with a void content P = 32% and surface condition Ra = 7, 76 mkm. The most stress is observed on the coating with inclusions, waviness, drips, shagreen. At these points there is a failure of the interference pattern, indicating the places of possible cracks. The same is true for other paints with different rheological properties.

A higher value of the coefficient of variation indicates a greater roughness. This will contribute to a more stressed state and less durability of the coatings [16, 17].

The probability of failure of protective and decorative coatings, depending on the presence of defects on the surface can be determined by the expression [12]:

$$P = 1 - e^{-\rho S} \quad (7)$$

where ρ - the concentration of defects;

S - surface area.

As seen from the formula (7) with the same surface area S covers the probability of failure increases with the concentration of defects.

The presence of defects on the surface of the coatings will undoubtedly affect the physico-mechanical properties of paint coatings. It is revealed that the elastoplastic character of the destruction is characteristic for the coatings studied (Figure 3, 4).

When increasing roughness of the coating surface is established of a decrease in strength and relative deformations of coating. When the roughness of coating based on paint PF-115 Ra = 0,74 mkm tensile strength of 57.7 kg /cm^2, the relative deformation = 44.3%, when the a roughness Ra = 1.74 mkm - 44.1 kg / cm^2 and 23% respectively. At increase the surface roughness are increased of the plastic deformations and are reduced elastic deformations. When the surface roughness of the coating Ra = 1,2 mkm proportion of elastic deformation of the component is 0.481, and plastic deformation of the component - 0.519, when roughness Ra = 1.74 micrometers, respectively, 0.281 and 0.719 (Figure 3).Coating based on PF - 115 paint is characterized mainly plastic deformation.

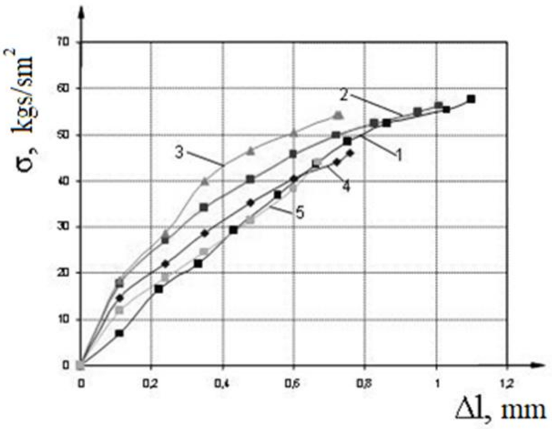

Figure 3. *Diagrams stretching coating based on the PF-115 paint*
1 - roughness of 1.2 microns; 2 - roughness of 1.37 microns;
3 - roughness of 1.45 microns; 4 - roughness of 1.54 microns;
5 - roughness of 1.74 microns

For coatings on the basis of the investigated compounds is observed flowing colorful character curve "tensile strength - roughness" with a sharp decline in strength to a certain value, constituting 45-55 kg /cm^2 at the roughness of the coating on the basis of the paint PF-115 Ra = 1,4-1, 6 micrometers. With further increase in the roughness of the coating surface is observed less reduction in tensile strength.

Regardless of the type of paint composition, the strength and relative deformations are reduced, the plastic deformation is increased and the elastic surfaces are reduced with increasing roughness (Figure 3).

At increase a roughness of coatings destruction has more fragile character.

A higher value of the coefficient of variation indicates an unstable process of staining. This predetermines lower resistance of coatings during operation and additional financial costs for the dyeing process. This must be taken into account when painting the building products and structures.

A sharp decrease in the strength and relative deformation of coatings based on PF-115 paint is observed at roughness of Ra =1.4 μm.

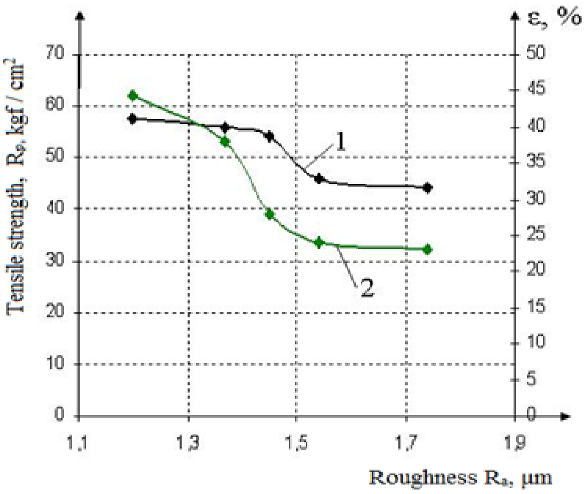

Figure 4. *The dependence of thetensile strength (1) and the relative elongation (2) from the coating surface roughness based on the PF-115 paint*

The dependence of the tensile strength on the roughness of the surface of the coatingcan is approximated by an expression of the form:

$$R_p = a \cdot e^{b \cdot R_a} \quad (8)$$

where Ra is the surface roughness, μm;

b is a coefficient that takes into account the degree of reduction in strength from Roughness, μm^{-1};

a - coefficient, characterizes the value of tensile strength, at Ra = 0 (ideal model).

The results of statistical data processing indicate that the model is adequate. The correlation coefficient between the calculated and experimental data is 0.99. The model makes it possible to calculate the value of cohesive strength of coatings depending on the roughness of its surface.

The presence of inclusions, shagreen, streaks, waviness on the surface of paint coatings, determines their stress state and endurance during exploitation. A more stressed state of the coating in places of greater roughness contributes to destroy the coating in these places during exploitation. It is established, that in the process of cyclic freezing-thawing the cracks appear locally and are formed near defects on the surface of the coating. In particular, on a coatings based on paint MA-15 with a roughness Ra = 0.23 mkm appeared cracks after 5 freeze-thaw cycles, and on a coating with a roughness Ra = 0.14 mkm - after 15 cycles tests. In the future, due to the destructive effect of moisture, the surface roughness increases, caused by the appearance of micro cracks, rashes, and bubbles. Similar regularities are also characteristic for other coatings. The obtained data correlate well with other indices of the protective and decorative properties of the coating (color change, gloss variation, chalking, mud retention, bronzing). For other types impact of environmental (humidification, UV-irradiation) on coatings the same patterns are observed.

4. Conclusions

It is established, that the quality of the appearance of coatings is determined by the method of applying paint, the porosity of the cement substrate. The statistical characteristics of the surface roughness of coatings are given. It was established, that the coloration process is more stable when the paint is applied on a cement substrate with a minimum porosity. Coatings are characterized by the smallest spreading of roughness. The researches allow to develop recommendations for increasing the resistance of coatings and to select the optimum rheological properties of paints depending on the porosity of the substrate. One should also take into account the method of staining (bruch, pour, airless method), depending on the porosity of the cement substrate. The significance of variability in the process of staining of building products and structures must be taken into account when choosing the method of applying paint, the porosity of the cement substrate. A model of the cohesive strength of coatings is presented, depending on the surface roughness. The model makes it possible to calculate the value of cohesive strength of coatings depending on the roughness of its surface.

Thus, during the painting, the enterprise must take into account also the statistical parameters of the staining process, which characterize its stability. It is possible to recommend, to organizations, firms, etc., engaged in the execution of finishing works, the introduction of the kaizen approach to the renewal of staining technology, based on continuous improvement of activities and providing for the use of statistical methods for managing product quality. We can recommend the application of the "six sigma" methodology. This methodology provides of decrease the range of indicators, increasing production culture.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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