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Integrated Electric Spark Testing of Continuity and Unacceptable Thinning of Dielectric Coatings

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Abstract—At present, the main method for detecting continuity defects in dielectric coatings is the electrospark method of nondestructive testing (NDT). However, minimum coating thickness requirements are applied to most modern coatings. It seems promising to carry out tolerance control of the testing of dielectric coatings in one technological process with control of their continuity due to changes in the existing testing methods and the method of forming the test voltage. Theoretical and experimental analysis of the processes of sparking occurring upon detection of through and nonthrough defects in dielectric coatings on electrically conductive substrates has been carried out. The minimum control voltages have been measured measured and calculated for the studied dielectric coatings, taking into account the detection of both through defects and unacceptable thinning. The application of a probabilistic approach to the detection of the above defects is proposed. It is shown that with a known value of the electrical strength of the coating, it is possible to detect both through and nonthrough defects with a calculated probability in coatings with a given test voltage.

Keywords: electrical strength, spark control, breakdown voltage, continuity, coating, thickness
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The problem of assessing the technical condition and extending the service life of dielectric anticorrosion and waterproofing coatings is of great practical importance; this is confirmed by the experience of operating various types of industrial metal products, including at pipeline transport infrastructure facilities.

One of the main requirements for such coatings is to ensure 100% continuity of the coatings [1–3]. However, in the case of violation of the coating technology and the rules for the operation of products, continuity defects can occur in the coatings such as paint skips, through and nonthrough pores, cracks, tears, punctures, etc.

In most cases, layer-by-layer deposition of dielectric coatings is assumed. In the case of violation of the application technology, the number of coating layers may not correspond to the declared one. Thus, there is an urgent problem of controlling the number of layers in the final system.

Most modern testing technologies involve measuring the final thickness of the coating with devices that make discrete measurements at various points in the structure, for example, electromagnetic thickness gauges. However, the implementation of continuous control of the coating thickness is a nontrivial technical problem.

One of the most common methods of nondestructive testing (NDE) of the continuity of dielectric coatings is the electrospark method, in which a high-strength electric field E is formed between the coating surface and the electrically conductive base to detect defects. Due to the fact that defective areas of the coating have an electrical strength lower than that of the defect-free coating, a spark discharge is formed in them given an appropriate electric field strength (Fig. 1).

Modern methods [1–5] for selecting the test voltage U_{tv} applied to the coating surface using an electrode make it possible to detect only through defects in coatings. At the same time, due attention is not paid to the relationship between the thickness d_{g} of tested coatings and their breakdown voltage U_{bv} for the problem of identifying unacceptably small thickness and nonthrough defects in the coatings. In this

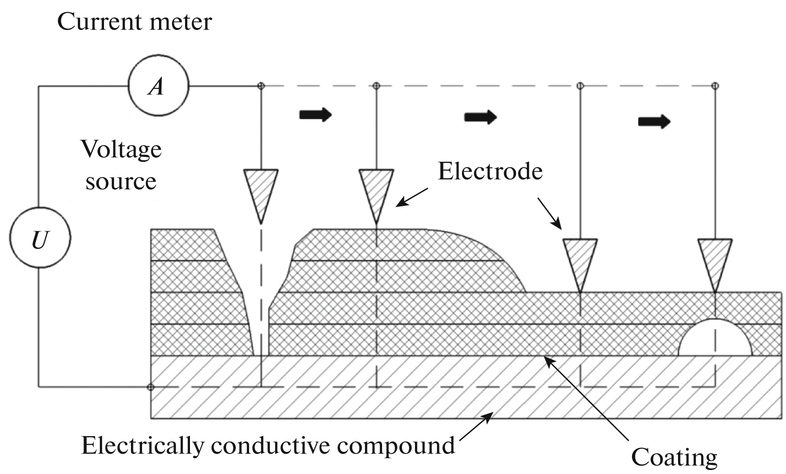

Fig. 1. Schematic representation of the principle of electrospark testing of dielectric coatings.

regard, it is important to develop a unified method for detecting not only discontinuities in coatings but also unacceptable thinning.

Thus, it is proposed in [6, 7] to estimate the geometric parameters of through defects in coatings by changing the electrical impedance when corona or spark discharges occur in them. A similar approach could also be applied to assess the leakage current through unacceptable thinning of the coating, however, the method based on the calculation and determination of the electrical resistance of the material cannot be applied to the areas of the coating where discharge processes occur [8].

For the problem under consideration, through defects in dielectric coatings are air interelectrode gaps, for which the breakdown voltage U_{bv} of the air gap for d_g from 5 μm to 50 mm in a uniform electric field can be calculated using the basic provisions of Townsend's theory of electrical breakdown [9, 10]. According to this theory, a spark discharge in a gaseous medium is formed due to the avalanche multiplication of free charge carriers in the interelectrode gap and the formation of an electrically conductive channel (streamer), the formation of which can be conditionally divided into the stages of formation of primary and secondary avalanches. For the formation of a primary avalanche of charge carriers (electrons), it is necessary that the free electrons present in the gas that fills the through defect of the coating receive energy from the external electric field created in the interelectrode gap (between the electrode and the electrically conductive base) greater than or equal to the ionization energy of gas atoms over the free path of an electron. Taking into account the coefficients of primary ionization α and attachment η, it is possible to determine the total number of electrons in an avalanche that has traveled a distance Δd [11],

$$n = n_0 e^{(\alpha-\eta)\Delta d}.$$

After the passage of the first avalanche in the interelectrode gap, the avalanche process can resume or die out. To resume the avalanche process (organization of a self-sustained discharge), at least one secondary effective electron is required, which can arise, including as a result of the passage of a primary avalanche, with an increase in U_{tv}.

The main provision of the theory is the condition of self-reliance of the discharge in places of discontinuity,

$$\gamma(e^{(\alpha-\eta)d_g} - 1) \geq 1, \qquad (1)$$

where γ is the coefficient of secondary ionization of electrons, α is the impact ionization coefficient, η is the number of free electrons, and d_g is the coating thickness.

The key element of a reliable electrospark NDT is to ensure the conditions for the independence of a spark discharge in places of coating defects (including discontinuities).

Dependence (1) shows that the passage of the primary avalanche requires the formation of at least one effective electron capable of igniting the secondary avalanche.

When considering the condition of self-reliance of the discharge in a uniform field (breakdown of the entire interelectrode gap), it is permissible to take η = 0 and bring expression (1) to the form

$$\eta(e^{\alpha d_g} - 1) = 1. \qquad (2)$$

It was experimentally established [10] that

$$\alpha = A_0 P e^{-\frac{B_0 P}{E}}, \tag{3}$$

where E is the intensity of a uniform electric field in the interelectrode gap, A_0 is a coefficient depending on the gas composition, B_0 is a coefficient depending on the gas ionization energy, and P is the gas pressure.

It follows from (2) and (3) that

$$\frac{\ln\left(1+\frac{1}{\gamma}\right)}{d_{\rm g}} = A_0 P e^{-\frac{B_0 P}{E}}. \tag{4}$$

As it is well known [12], for a homogeneous field $E = U_{\rm bv}/d_{\rm g}$, therefore, we substitute this expression into (4) to obtain

$$\ln\left(1+\frac{1}{\gamma}\right) = A_0 P d_{\rm g} e^{-\frac{B_0 P d_{\rm g}}{U_{\rm bv}}}. \tag{5}$$

Taking the logarithm of (5), we obtain

$$\frac{B_0 P d_{\rm g}}{U_{\rm bv}} = \ln\frac{A_0 P d_{\rm g}}{\ln\left(1+\frac{1}{\gamma}\right)}. \tag{6}$$

Since we are interested in $U_{\rm bv}$, to determine it, we transform (6) to the form

$$U_{\rm bv} = \frac{B_0 P d_{\rm g}}{\ln\frac{A_0 P d_{\rm g}}{\ln\left(1+\frac{1}{\gamma}\right)}}. \tag{7}$$

It follows from (7) that at a constant ambient air temperature in a uniform field we have $U_{\rm bv} = f(Pd_{\rm g})$, and at a quasiconstant atmospheric pressure, $U_{\rm bv} = f(d_{\rm g})$ (Fig. 2).

At the same time, standardized methods for determining the test voltage taking into account the inhomogeneities of the electric field during the testing process offer the calculation of $U_{\rm tv}$ based on the empirical dependence [2, 3] (see Fig. 2)

$$U_{\rm tv} = M\sqrt{d_{\rm g}}, \tag{8}$$

where M is a constant empirical coefficient depending on $d_{\rm g}$ ($M = 3294$ for coatings with a thickness of $d_{\rm g} < 1$ mm and $M = 7843$ for $d_{\rm g} > 1$ mm).

As can be seen from Fig. 2, standardized methods for calculating the test voltage are intended solely for the detection of through defects in the coating. To reveal unacceptable thinning of coatings by the electrospark method, it is necessary to consider the processes of breakdown of solid dielectrics.

The electrical strength of dielectrics can be calculated depending on their structure and energy characteristics of the material [15].

An empirical dependence of the breakdown voltage of the coating $U_{\rm bv}$ is proposed in [13] for a wide range of dielectric coatings,

$$U_{\rm bv} = \frac{K}{d_{\rm g}} K_{\rm B}(A_{\rm c}^0)^{1.1} \exp\left(\frac{a}{b+\log(b)} + \frac{m}{n+\log(\tau)}\right), \tag{9}$$

where K is a proportionality factor depending on $d_{\rm g}$, τ is the duration of the applied voltage, $K_{\rm B}$ is the breakdown probability, $A_{\rm c}^0$ is the channeling energy, and a, b, n, and m are some constants depending on the composition of the dielectric.

The resulting formula can be used in calculating the dielectric strength of dielectrics with a thickness of 0.01 to 40 mm for an applied voltage pulse duration $\tau = 0.1–10$ μs.

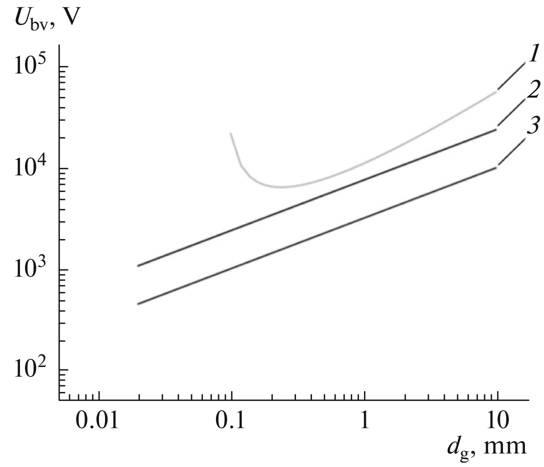

Fig. 2. Design values of U_{bv}: *1*, $U_{bv}(d_g)$ by formula (7) for atmospheric air under normal conditions, *2*, $U_{bv}(d_g)$ by formula (8) for $d_g > 1$ mm, and *3*, $U_{bv}(d_g)$ by formula (8) for $d_g < 1$ mm.

Table 1 lists the values of U_{bv} for a number of solid dielectrics obtained experimentally and calculated using the above formulas for samples with a thickness of $d_g = 0.1$ mm [14].

The estimation of U_{bv} according to (9) is possible for one-component or multilayer coatings, the parameters of which can be found in the reference literature, for example, anticorrosion coatings of pipelines. At the same time, it should be taken into account that the parameters of multicomponent coatings (for example, paint and varnish) required for the calculation, as a rule, are not standardized. Therefore, the U_{bv} of multicomponent coatings for which the U_{bv} cannot be determined by calculation can be determined experimentally. For the experimental determination of U_{bv}, it is proposed to use a coating that is identical or close to the tested one in composition and thickness deposited on a metal base.

As an example, the results of an experiment on determining U_{bv} are given, in which sheets of foil Textolite® and aluminum were used as bases to which a paint and varnish coating (LCP)—MLS 306 enamel—was applied.

After manufacturing the samples (applying three, six, and nine layers of coating on the surface of the base), the thickness was measured at the check points at which the breakdown voltage was determined. The applied voltage was increased until the coating breakdown, the value of U_{bv} was recorded using a DSO-X 2002A oscilloscope. As a result, the dependence $U_{bv}(d_g)$ was obtained; it is shown in Fig. 3.

As can be seen from Fig. 3, the obtained values of U_{bv} have a fairly large spread. Presumably, this is due to the formation of the discharge at the point with the smallest coating thickness and some scatter in the coating parameters [16, 17]. For this reason, it is required to evaluate the probability of detecting unacceptable thinning of the coating depending on U_{tv} and d_g.

For this, an algorithm was applied that is based on constructing a regression curve for the dependence $U_{bv}(d_g)$ and constructing normal distribution functions with specified parameters on its basis [18, 19].

In the area under study, the dependence $U_{bv}(d_g)$ has a quasilinear form. Consequently, according to the experimental data obtained, a linear regression of the form $U = kd + b$ was constructed for which the func-

Table 1. Design and experimental values of electrical strength U_{bv} for dielectric materials with thickness $d = 0.1$ mm

Coating material	U_{bv}, kV	
	experimental values	design values
Polyethylene	6.75–7	6.2
Polystyrene	5.5–7.3	4.3
Fluoroplast-4	3.5	4

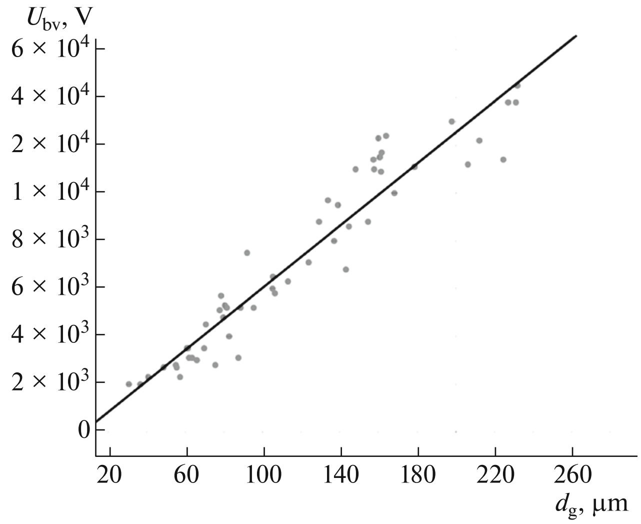

Fig. 3. Dependence of breakdown voltage of coatings U_{bv} on coating thickness d_g.

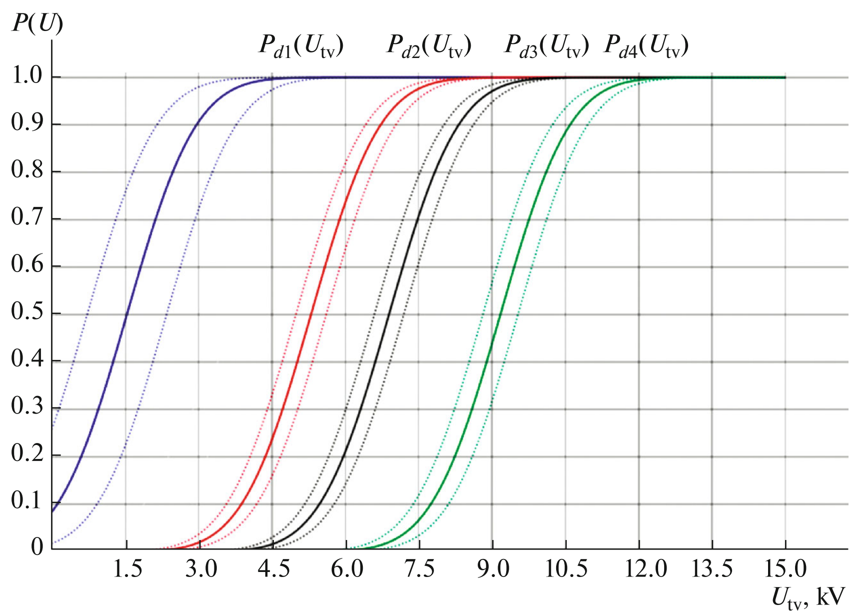

Fig. 4. Distribution of coating breakdown probability depending on the applied voltage for $d_1 = 38$ μm, $d_2 = 89$ μm, $d_3 = 113$ μm, and $d_4 = 148$ μm.

tion of the normal (Gaussian) distribution of the probability of spark discharge formation versus the value of U_{tv} was constructed (see Fig. 3),

$$P(U_{tv}) = \frac{1}{\sqrt{2}\sigma}\int_{-\infty}^{U_{tv}} e^{-\frac{(t-\mu)^2}{2\sigma^2}}dt,$$

where d_g is the coating thickness, U_{tv} is the test voltage, k and b are parameters of the regression curve, μ is the expectation, and σ is the r.m.s. deviation.

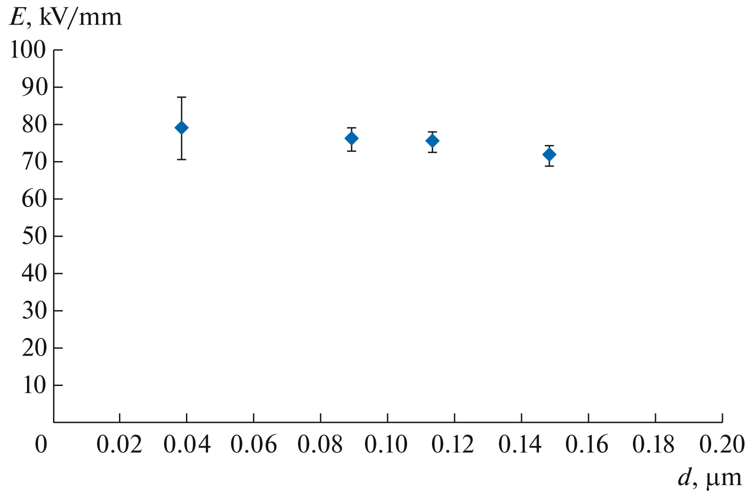

Fig. 5. Dependence of the electrical strength of the coating E_b on its thickness for the samples under study.

The boundaries of the confidence interval $P(U_{tv})$ for the regression model (see Fig. 3) in accordance with [20] are

$$P_{\pm}(U_{tv}) = P(U_{tv}) \pm t_P\sqrt{D}\sqrt{\frac{1}{n} + \frac{(\ln U_{tv} - \bar{U}_{tv})^2}{\sum_{i=1}^{n}(\ln U_{tvi} - \bar{U}_{tv})^2}},$$

where n is the number of measurements, t_P is Student's coefficient for 95% confidence probability and $(n - 2)$ degrees of freedom, and D is the variance of breakdown voltage values.

The graph of the dependence of the probability of detecting a defect $P(U_{bv})$ characterizes the reliability of the NDT. The graph, which is a sigmoid function, shows the boundaries of the interval with a given confidence probability (shown by the dotted line). Obviously, with an increase in d_g, the characteristic $P(U_{bv})$ shifts to the right. Also, when carrying out tolerance control of the coating (identifying places of unacceptable thinning), it is recommended to construct the dependence $P(U_{bv})$ for the confidence probability of detecting a defect of 0.9 (90%). Therefore, it is possible to determine the electrical strength of the coating E_b for a defect detection probability equal to 90% for each investigated coating thickness (Fig. 5).

The experimental data show that the calculated value of E_b in the specified range of thicknesses is 75.4 ± 8.2 kV. Taking into account the fact that the electric strength is almost constant in the specified range of thicknesses, the probability of detecting a defect of a given thickness (based on the electric strength of the coating) will be 0.8 (80%).

Thus, with a known value of the electrical strength of the coating (calculated or determined experimentally), it is possible to detect unacceptable thinning with a given probability by testing with a test voltage the value of which is equal to $U_{tv} = E_b/d_g$.

CONCLUSIONS

The paper presents a theoretical and experimental analysis of the processes of sparking in relation to the problems of identifying through and nonthrough defects in dielectric coatings on electrically conductive substrates. The minimum test voltages for through defects in coatings are calculated and the impossibility of using existing NDT methods to detect nonthrough defects in coatings is demonstarted. The minimum test voltages of the studied dielectric coatings are measured and calculated taking into account the need to identify both through defects and unacceptable thinning. It is proposed to use a probabilistic approach to detect the described defects. It is shown that with a known value of the electrical strength of the coating, it is possible to detect both through and nonthrough defects in coatings at a given test voltage with a calculated probability.

The results obtained make it possible to develop a test procedure that expands the range of applicability of the method and increases the reliability of the control results.

REFERENCES

1. *GOST (State Standard) R51164-98. Main steel pipelines. General requirements for corrosion protection*, Moscow: Izd. Stand., 1998.
2. *GOST (State Standard) 34395-2018. Paintwork materials. Electrospark method for testing the continuity of dielectric coatings on conductive bases*, Moscow: STANDARTINFORM, 2018.
3. *ASTM G62-14.* Standard test methods for holiday detection in pipeline coatings.
4. Erekhinskii, B.A. and Pakhomov, A.V., *Sovremennye tekhnologii diagnostiki ob"ektov dobychi gaza i gazovogo kondensata. Primenyaemaya tekhnika i oborudovanie* (Modern Technologies for Diagnosing Gas and Gas Condensate Production Facilities. Applied Machinery and Equipment), Voronezh: Voronezh. Oblastn. Tipogr, 2017.
5. Davies, M.A.S., Holiday detection: what is the correct test voltage?, *Anti-Corros. Methods Mater.*, 1983, vol. 30, pp. 4—12.
6. Gadzhiev, Ya.M. and Ibragimova, E.N., Experimental investigation of measuring the dimensions of crackles of the silicate enamel coating of the pipe, *Defektoskopiya,* 2020, no. 1, pp. 61–65.
7. Ibragimov, N.Yu. and Ibragimova, E.N., Flaw detector crack gauge for silicate pipe coatings, *Defektoskopiya,* 2017, no. 11, pp. 55–57.
8. *Nerazrushayushchii kontrol'. Elektricheskii kontrol' / Spravochnik v 7 t.* (Nondestructive Testing. Electrical Testing. A Handbook in 7 Vols.), Klyuev, V.V., Ed., Moscow: Mashinostroenie, 2004.
9. Raizer, Yu.P., *Fizika gazovogo razryada / Uchebnoe rukovodstvo* (Gas Discharge Physics. A Tutorial), Moscow: Nauka, 1992.
10. Tren'kin, A.A., Almazova, K.I., Belonogov, A.N., Borovkov, V.V., Gorelov, E.V., Morozov, I.V., and Kharitonov, S.Yu., Formation of the microchannel structure of a spark discharge in air in the gap spike-plane, *Zh. Tekh. Fiz.,* 2020, vol. 90, no. 12.
11. Smirnov, A.S., *Prikladnaya fizika. Fizika gazovogo razryada / Uchebnoe posobie* (Applied Physics. Physics of the Gas Discharge. A Tutorial), St. Petersburg: Izd. SPbGTU, 1997.
12. Meek, J.M. and Craggs, J.D., *Electrical Breakdown of Gases,* Oxford: Clarendon Press, 1953. Translated under the title: *Elektricheskii proboi v gazakh,* Moscow: Izd. Inostr. Lit., 1960.
13. Vazhov, V.F., Lavrinovich, V.A., and Lopatkin, S.A., *Tekhnika vysokikh napryazhenii: kurs lektsii* (High Voltage Techniques: a Lecture Course), Tomsk: Izd. Tomsk. Politekh. Univ., 2006.
14. Vorob'ev, G.A., Pokholkov, Yu.P., Korolev, Yu.D., et al., *Fizika dielektrikov (oblast' sil'nykh polei) / Uchebnoe posobie* (Physics of Dielectrics (Strong Fields). A Textbook), Tomsk: Izd. Tomsk. Politekh. Univ., 2003.
15. Grigor'ev, A.N., Pavlenko, A.V., Il'in, A.P., and Karkaukohov, E.I., Electric discharge over the surface of a solid dielectric. Part 1. Features of the development and existence of a surface discharge, *Izv. Tomsk. Politekh. Univ.,* 2006, no. 1, pp. 66–69.
16. Starikova, N.S. and Red'ko, V.V., The study of methods for monitoring the integrity of insulation in the field of weak and strong electric fields, *Vestn. Nauki Sib.,* 2013, no. 3 (9), pp. 55–59.
17. Galeeva, N.S., Increasing the information content of testing cable products based on the integrated use of electrospark and electrocapacitive methods, *Cand. Sci. Dissertation,* Tomsk Polytech. Univ, 2017.
18. Chertishchev, V.Yu., Estimation of the probability of detecting defects by acoustic methods depending on their size in PCM structures for the output testing data in the form of binary values, *Aviats. Materi. Tekhnol.,* 2018, no. 3 (52).
https://doi.org/10.18577/2307-6046-2018-0-3-65-79
19. Boichuk, A.S., Generalov, A.S., Dalin, M.A., and Stepanov, A.V., Probabilistic assessment of the reliability of the results of ultrasonic nondestructive testing of PCM structures used in the aviation industry, *Remont. Vosstanov. Mod.,* 2013, no. 9, pp. 36–39.
20. Lebedev, A.M., The study of the reliability of tolerance testing, *Nauchn. Vestn. MGTU GA,* 2005, vol. 86, no. 4, pp. 65–70.