Tests of paint and varnish ice-resistant protective coatings of ice class vessels

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Abstract. The study examines the regularities of the outer coatings deterioration of ice class vessels and icebreakers, as well as the effect of ice-resistant protective coatings on deterioration rates. As the initial data, the results of measurements of residual thicknesses from the DEFHULL computer database were used. A comparison of the normative values of the outer coatings deterioration rates for ice class vessels presented in the current version of the RMRS Rules and the values obtained as a result of processing the DEFHULL database data was carried out. The results and conclusions were used in developing the proposals for amending and supplementing the RMRS Rules regarding the purpose of corrosion and abrasion surcharges when determining the thickness of the outer coatings of ice class vessels.

1. Introduction
Protective materials and coatings are a promising area for improving the reliability, safety and functional efficiency of vessels and marine equipment. A large number of paint and varnish coatings have been developed and are being used in practice, which make it possible to protect the vessel hulls for various purposes from corrosion. In this case, the choice of protection system largely depends on the type and purpose of the vessel.

A use of traditional systems and paint and varnish coatings to protect against corrosion and abrasion does not fully solve this problem. On ice class vessels and icebreakers, the degree of destruction of the underwater hull, and especially in the area of the ice belt, is extremely high, which under the impact of ice leads to corrosion and erosion destruction of the sheets of the outer skin of the hull, lower ice permeability, increased fuel consumption and increased dock repair work.

The rapid deterioration of the paint and varnish coatings is due to the fact that the group of vessels under consideration shows a significant unevenness in the deterioration of the outer skin sheets both along the length and on the side height.

Only some types of coatings can provide effective protection. To protect the sheets of the outer skin of the icebreakers and ice class vessels against corrosion and abrasion, special coatings and protection systems have been developed and are used. Typically, such coatings have special properties, are resistant to prolonged abrasion and impact of ice and, as a rule, are certified by the classification societies as ice-resistant.

An ice-resistant coating is considered to be a coating that is capable of protecting the outer skin of the vessel hull from external influences in ice navigation conditions with characteristics that meet the...
requirements specified in the Rules for the Classification and Construction of Ships, Part XIII [1] of the Russian Maritime Register of Shipping (RMRS).

Table 1. Requirements of the RMRS Rules for ice-resistant coatings.

| No | Indicators                                                                 | Values                                                      |
|----|---------------------------------------------------------------------------|-------------------------------------------------------------|
|    |                                                                           | For icebreakers of all ice classes | For ice class vessels of Arc 4 and higher |
|    |                                                                           | Class I       | Class II       | Class I       | Class II       |
| 1  | Durability according to ISO 12944-6 for the corrosivity category Im2       | large          | large          |               |                |
|    | according to ISO 12944-2                                                  |                |                |               |                |
| 2  | Adhesion determined by the method of trellised notches according to ISO    | no more than 3 points | no more than 3 points |
|    | 2409 or the method of crosswise notches according to ISO 16276-2 after    |                |                |               |                |
|    | tests for resistance to low temperatures depending on the thickness and   |                |                |               |                |
|    | type of ice- Adhesive strength according to ISO 4624                       |                |                |               |                |
| 3  | Adhesive strength according to ISO 4624                                    | more than 16 MPa | more than 10 MPa | more than 10 MPa | more than 8 MPa |
| 4  | Abrasion resistance after 1000 test cycles on Taber abrasimeter (CS-17    | no more than 80 mg | no more than 120 mg | no more than 120 mg | no more than 160 mg |
|    | wheel)                                                                     |                |                |               |                |
| 5  | Impact strength according to ISO 6272                                      | not less than 5 J | not less than 5 J |               |                |
| 6  | Resistance to cathodic peeling according to ISO 15711 (method A) for      | less than 5 mm after 3 months of tests, | less than 5 mm after 3 months of tests, |
|    | coatings compatible with cathodic protection                                | less than 8 mm after 6 months of tests                      | less than 10 mm after 6 months of tests |
| 7  | Coefficient of friction on ice                                              | no more than 0,03 | no more than 0,08 | no more than 0,03 | no more than 0,08 |

This status also means that the use of such coatings will reduce the required thickness of vessel structures, which decreases the weight of the hull construction, reduces construction costs and increases the efficiency of the vessel.

The goal of this study is to test the strength and friction properties of ice-resistant paint and varnish coatings (IPVC).

The main tasks:
- Determination of friction indicators of samples with IPVP on ice for compliance with the requirements of part 2.5.7 of the RMRS Rules [1];
- Determination of the strength indicators of IPVC during tensile and bending of the sample in order to determine the stresses at which cracking and/or peeling of the ice-resistant protective coating from a metal surface is observed.

2. Requirements for samples, conditions and means of testing

Tests of samples with IPVC were performed in a specialized laboratory equipped with a freezer (climatic) chamber and providing standard test conditions at a temperature of minus 20°C. For testing, coated samples were preliminarily held at a temperature of minus 20°C for at least 15 minutes, relative humidity of the surrounding air was not more than 85%, and atmospheric pressure was 1 bar.

For friction tests, metal samples with IPVC (plates) 250×130×3 mm in size were used. The shape and size of the samples comply with the requirements of 2.5.7 of XIII part (“Materials”) of the RMRS Rules [1].

The shape and dimensions of samples with IPVC designed for tensile testing meet the requirements of 2.2.2 of XIII part (“Materials”) of the RMRS Rules [1] and GOST (State Standard) 1497-84 [2].
The type and geometrical dimensions of samples for tensile testing with IPVC are in Figure 1.

![Sample for tensile testing](image1)

**Figure 1.** Sample for tensile testing.

Dimensions of the samples:
- $a = 3$ mm - thickness of the working part of the sample;
- $b = 20$ mm - width of the working part of the sample;
- $L_0 = 45$ mm - length of calculated part of the sample;
- $L_c = 60$ mm - length of working part of the sample;
- $R = 25$ mm - radius of transition from the working part to the sample head.

For each of the three tests, it is necessary to have three coated samples.

The shape and dimensions of the samples for bending tests must comply with the requirements of 2.2.5 of XIII part (“Materials”) of the RMRS Rules [1] and GOST 14019-80 [3].

Test samples were rectangular coated metal plates.

Dimensions of samples:
- $a = 3$ mm - thickness of the working part of the sample;
- $b = 20$ mm - width of the working part of the sample;
- $L = 70$ mm - length of sample.

For each of the three tests, three coated samples were used.

The appearance of the samples intended for testing for friction, tension and bending is in Figure 2.

![Test samples](image2)

**Figure 2.** Test samples:
- a - to determine the coefficient of friction; b - for tensile tests; c - for bending tests.

For experiments to determine the friction indicators of samples coated on ice were used:
- climate chamber;
- a laboratory unit equipped with a compartment (reservoir) for placing the fresh ice, including a mechanism that provides a change in the vertical, pressing force on the sample coated on ice and providing a longitudinal displacement of the sample relative to ice at a given speed, a device that fixes the friction force during longitudinal movement of the sample relative to ice;
- a personal computer with installed software that records and fixes the vertical forces pressing the coated sample on ice and the friction force during longitudinal movement of the sample relative to ice.

To ensure experiments on determining the strength indicators of IPVC under tensile and bending of samples, the following were used:
- climate chamber;
- universal testing machine - AG-XPlus 100 kN;
- personal computer with specialized software;
- video recorder.

The appearance of the test equipment used to perform the experiments is in Figures 3, 4.

**Figure 3.** Equipment for determining the coefficient of friction of samples on ice.

**Figure 4.** Universal testing machine - AG-XPlus 100 kN.
3. Indicators determined under the tests

When determining the parameters during the friction tests, the coated sample was fixed in a laboratory unit; a vertical force was applied to it, pressing it to the ice. Next, the mechanism of longitudinal movement of the sample with a pre-adjusted speed took place. Due to the frictional forces between the contacting surfaces of the sample and ice, they can remain stationary relative to each other until the force that moves the sample becomes equal to or exceeds the static friction force between the surfaces. The maximum initial value of the force was recorded, which is a component necessary for calculating the coefficient of rest friction.

The value of force was also recorded with constant movement of surfaces relative to each other at a distance of not less than 130 mm. This force is equal to the sliding friction force, and is needed to maintain the movement of surfaces relative to each other. Tests were carried out at least 3 times in accordance with 2.5.7.3 of XIII part (“Materials”) of the RMRS Rules [1].

The registration and fixing of the vertical forces pressing the coated sample to ice and the friction forces during the longitudinal displacement of the coated sample relative to ice was carried out using specialized software.

The coefficient of rest friction is calculated as follows:

\[ S = \frac{TS}{N} \]

where \( TS \) - value on the scale of the device, corresponding to the beginning of movement, H; \( N \) - vertical force acting on the sample, N.

The sliding friction coefficient is calculated as follows:

\[ K = \frac{TK}{N} \]

where \( TK \) - average value on a scale corresponding to constant sliding, N.

The methodology for determining the error of experimental results when using the device is adopted in accordance with ISO 5725 [4].

After the tests, the sample was inspected. The test results were issued in the form of a test report in the prescribed form.

During tensile and bending tests of the samples, the forces and deformations during coating failure were recorded in accordance with ISO 4628-4 [5] and ISO 4628-5 [6]. For each indicator for the characterization of cracking and/or peeling of coatings were fixed (Tables 2, 3):

- under the sample stretching - stress and relative elongation;
- Under the bending - stress and deformation of the sample.

**Table 2.** Diagram of indicators for the number of cracks and the area of exfoliation.

| Indicator | Number of cracks according to ISO 4628-4 | Peeling area, % according to ISO 4628-5 |
|-----------|----------------------------------------|----------------------------------------|
| 2         | Few, i.e. small but significant number of cracks | 0.3                                    |
| 3         | Moderate number of cracks               | 1                                      |
| 4         | Significant number of cracks            | 3                                      |
| 5         | Dense crack structure                   | 15                                     |

**Table 3.** Diagram of indicators for designating the size of cracks and designating the size of the areas of exfoliation.

| Indicator | Crack size according to ISO 4628-4 | Peel area size (largest size) according to ISO 4628-5 |
|-----------|------------------------------------|------------------------------------------------------|
| 2         | Barely visible with normal correction | Up to 3 mm                                          |
| 3         | Clearly visible with normal correction | Up to 10 mm                                         |
| 4         | Large cracks, usually with a width of up to 1 mm | Up to 30 mm                                         |
| 5         | Very large cracks, usually with a width greater than 1 mm | More than 30 mm                                     |
After the test, the sample was inspected. The test results were recorded in the form of protocols in the prescribed form.

4. Sample Modes and Tests
Friction tests were carried out for 3 values of vertical (clamping) force and at 3 speeds of longitudinal displacement of the coated sample relative to ice at 120, 150 and 180 mm/min.
In tensile and bending tests, the loading speed of the coated samples was constant, the possible deviations of the speed during the test were taken to increase without sharp changes, according to ISO 6892-84.
Examples illustrating the progress of testing the coated samples are in Figures 5-7.

![Figure 5](image1.jpg)
![Figure 6](image2.jpg)

**Figure 5.** Test Examples: a - for friction; b - to bend.

**Figure 6.** An example of a tensile test of sample.
5. The effect of protective coatings on the deterioration rate of the outer coatings of vessels and icebreakers

5.1 Determination of friction

The test results of the ice-resistant paint and varnish coating when driving on ice in full are in Tables 4 - 6 (summary data on the measured coefficients of initial friction of rest, as well as data on the coefficient of sliding friction).

**Table 4. Definitions of friction coefficients for Sample No.1.**

| Indicators | The longitudinal displacement rate of the sample relative to ice, mm/min | Vertical (clamping) force N, N | Measurement error |
|------------|---------------------------------------------------------------|-------------------------------|------------------|
| Friction force corresponding to the beginning of the movement $T_s$, N | 120 | 7,255 | 7,518 | 10,384 | ± 0,5% |
| | 150 | 8,320 | 10,085 | 10,042 |
| | 180 | 5,792 | 10,740 | 12,150 |
| Friction force corresponding to slip $T_k$, N | 120 | 4,179 | 4,830 | 6,910 | ± 0,5% |
| | 150 | 3,816 | 5,830 | 6,620 |
| | 180 | 3,983 | 5,573 | 6,927 |
| The coefficient of friction corresponding to the beginning of movement $\mu_s=T_s/N$ | 120 | 0,114 | 0,090 | 0,100 | ± 0,5% |
| | 150 | 0,131 | 0,120 | 0,096 |
| | 180 | 0,091 | 0,128 | 0,117 |
| The coefficient of friction corresponding to the slip $\mu_k=T_k/N$ | 120 | 0,066 | 0,058 | 0,066 | ± 0,5% |
| | 150 | 0,060 | 0,070 | 0,064 |
| | 180 | 0,063 | 0,067 | 0,066 |

$t$ - Student’s distribution, $t_{95\%}$

The average coefficient of friction corresponding to the beginning of movement $\mu_s$ 0,110

Standard deviation on general population $\mu_s$ 0,016

Confidence interval limits, $\pm \Delta\mu_s$ 0,036

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**Figure 7.** Samples after testing 

a - on tension; b, c - on bend.
### Average coefficient of friction under constant sliding $\mu_K$

| Indicators                                                                 | The longitudinal displacement rate of the sample relative to ice, mm/min | Vertical (clamping) force $N$, N | Measurement error |
|----------------------------------------------------------------------------|---------------------------------------------------------------------------|---------------------------------|-------------------|
| Friction force corresponding to the beginning of the movement $T_S$, N     | 120                                                                       | 6,656                           | 12,450            |
|                                                                            | 150                                                                       | 6,042                           | 10,781            |
|                                                                            | 180                                                                       | 4,848                           | 13,200            |
| Friction force corresponding to slip $T_K$, N                               | 120                                                                       | 4,079                           | 6,546             |
|                                                                            | 150                                                                       | 4,264                           | 5,523             |
|                                                                            | 180                                                                       | 3,958                           | 5,479             |
| The coefficient of friction corresponding to the beginning of movement $\mu_S = T_S/N$ | 120                                                                       | 0,105                           | 0,120             |
|                                                                            | 150                                                                       | 0,095                           | 0,103             |
|                                                                            | 180                                                                       | 0,076                           | 0,127             |
| The coefficient of friction corresponding to the slip $\mu_K = T_K/N$       | 120                                                                       | 0,064                           | 0,063             |
|                                                                            | 150                                                                       | 0,067                           | 0,053             |
|                                                                            | 180                                                                       | 0,062                           | 0,053             |
| $t$ - Student’s distribution, $t_{95\%}$                                    |                                                                           |                                 | 2,262             |
| The average coefficient of friction corresponding to the beginning of movement $\mu_S$ |                                                                           |                                 | 0,105             |
| Standard deviation on general population $\mu_S$                           |                                                                           |                                 | 0,014             |
| Confidence interval limits, $\pm \Delta \mu_S$                            |                                                                           |                                 | 0,032             |
| Average coefficient of friction under constant sliding $\mu_K$             |                                                                           |                                 | 0,061             |
| Standard deviation on general population $\mu_K$                           |                                                                           |                                 | 0,005             |
| Confidence interval limits, $\pm \Delta \mu_K$                            |                                                                           |                                 | 0,011             |

### Table 5. Definitions of friction coefficients for Sample No. 2.

### Table 6. Definitions of friction coefficients for Sample No. 3.
corresponding to the slip\n\[ \mu_k = \frac{T_k}{N} \]
\[
\begin{array}{cccc}
150 & 0.062 & 0.060 & 0.059 \\
180 & 0.070 & 0.062 & 0.061 \\
\end{array}
\]

\[ t \text{- Student's distribution, } t_{95\%} = 2.262 \]

The average coefficient of friction corresponding to the beginning of movement \( \mu_S \) was 0.100

Standard deviation on general population \( \mu_S \) was 0.008

Confidence interval limits, \( \pm \Delta \mu_S \) was 0.017

Average coefficient of friction under constant sliding \( \mu_K \) was 0.063

Standard deviation on general population \( \mu_K \) was 0.004

Confidence interval limits, \( \pm \Delta \mu_K \) was 0.008

Summarized data on the results of tests of ice-resistant paint and varnish coating when the sample moves on ice (determination of the friction coefficient) are in Table 7.

**Table 7.** The results of the tests of IPVC when determining the coefficient of friction on ice.

| Number of sample | Friction of rest \( \mu_S \) | Sliding friction \( \mu_K \) |
|------------------|-----------------------------|-----------------------------|
| 1                | 0.110±0.036                 | 0.064±0.008                 |
| 2                | 0.105±0.032                 | 0.061±0.011                 |
| 3                | 0.100±0.017                 | 0.063±0.008                 |
| **Average**      | **0.105±0.028**             | **0.063±0.009**             |

As a result of the experiments, it was found that the tested IPVC in terms of the coefficient of sliding friction on ice corresponds to Class II in accordance with 6.5.3 of the Rules for the Classification and Construction of Ships, part XIII (“Materials”).

5.2 Determination of strength indicators

Figures 8, 9 show examples of control of test results using the specialized software integrated into the working environment of a universal testing machine - AG-XPlus 100 kN.

![Figure 8. Example of tensile test of sample coated.](image-url)
Figure 9. An Example of bending test of sample coated.

The results of the IPVC test under tension and bending of the samples are in Tables 8, 9.

Table 8. Results of stretching the coated samples.

| Indicators          | Crack and Peel Index | Sample No.4 | Sample No.5 | Sample No.6 | Average |
|---------------------|----------------------|-------------|-------------|-------------|---------|
| Tension, MPa        |                      |             |             |             |         |
| 2                   | 279.7                | 278.5       | 276.4       | 278.2       |
| 3                   | 353.2                | 326.6       | 326.5       | 335.4       |
| 4                   | 381.1                | 381.2       | 377.7       | 380.0       |
| 5                   | 401.1                | 401.2       | 401.6       | 401.3       |
| Relative elongation, %|                      |             |             |             |         |
| 2                   | 6                    | 6           | 6           | 6           |
| 3                   | 10                   | 10          | 10          | 10          |
| 4                   | 15                   | 15          | 15          | 15          |
| 5                   | 25                   | 25          | 25          | 25          |

Table 9. Results of bending of coated samples.

| Indicators                       | Crack and Peel Index | Sample No.7 | Sample No.8 | Sample No.9 | Average |
|----------------------------------|----------------------|-------------|-------------|-------------|---------|
| Tension, MPa                     |                      |             |             |             |         |
| 2                                | 313.5                | 311.2       | 318.8       | 314.6       |
| 3                                | 347.7                | 346.6       | 350.5       | 348.3       |
| 4                                | 452.7                | 454.7       | 456.2       | 454.6       |
| 5                                | 472.9                | 475.6       | 479.5       | 476.1       |
| Bending angle of the sample, degrees |                      |             |             |             |         |
| 2                                | 5                    | 4           | 6           | 5           |
| 3                                | 17                   | 16          | 19          | 17          |
| 4                                | 31                   | 31          | 31          | 31          |
| 5                                | 45                   | 45          | 42          | 44          |

We note that the strength parameters of the paint and varnish coating during tensile and bending of samples (determination of stresses at which cracking and/or peeling of the ice-resistant protective coating from a metal surface is observed) are currently not standardized and are not regulated by the requirements.
of the RMRS Rules. The tests were performed in accordance with the Terms of Reference for tests for a complete study of the characteristics and quality of the developed coating. The test results showed that the coating breaks at stresses close to the yield strength of the sample material.

6. Conclusion
The results of the study:
- a test program for the strength and friction properties of an ice-resistant paint and varnish coating has been developed;
- a complex of strength and friction tests was carried out;
- the coefficients of friction of samples with IPVC on ice were determined for compliance with the requirements of 2.5.7 of the Rules for the classification and construction of marine vessels, part XIII "Materials" of RMRS [1];
- the strength parameters of the paint and varnish coating during tensile and bending of the samples have been determined in order to identify the stresses at which cracking and/or peeling of the ice-resistant protective coating from a metal surface was observed.

As a result of the performed experiments, it was found that the tested IPVC on the coefficient of sliding friction on ice \((0.063 \pm 0.009)\) corresponds to Class II according to 6.5.3 of the Rules for the classification and construction of ships, part XIII “Materials” and can be used as an ice-resistant coating for the outer skin of vessels belonging to Group 1 (icebreakers of all ice classes) and Group 2 (vessels of ice classes Arc4 and above).

The results of the tests showed that the coating begins to collapse at stresses close to the yield strength of the material of the samples, which indicates the possibility of using the coating under stress, characteristic for the region of elastic deformation of the outer skin and arising from ice impact.

References
[1] Rules for the Classification and Construction of Ships 2020 (part XIII “Materials”, Russian Maritime Register of Shipping)
[2] GOST 1497-84 (ISO 6892-84) 1987 Metals. Tensile test methods
[3] GOST 14019-80 1980 Metals. Bending test methods
[4] ISO 5725 Accuracy (correctness and precision) of measurement methods and results
[5] ISO 4628-4 Paints and varnishes. Assessment of the degree of destruction of coatings. Designation of the number and size of defects and the intensity of uniform changes in appearance. Part 4. Assessment of the degree of cracking
[6] ISO 4628-5 Paints and varnishes. Assessment of the degree of destruction of coatings. Designation of the number and size of defects and the intensity of uniform changes in appearance. Part 5. Assessment of the degree of exfoliation