Recognition of underframe corrosion of automobile bodies using infrared thermography methods

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Abstract. The article describes the methodology of experimental studies on the detection and quantification of under-paint corrosion of metal parts with the use of infrared thermography. This study provides a description of the process of reducing the performance of a metal structure over time on the basis of the mathematical apparatus of the theory of catastrophe. The dependence of the diagnostic signal on the color of the paint coat, which characterizes the presence of a hidden corrosion defect is presented. Suggestions for the implementation of this method to evaluate the degree of corrosion damage in control objects with various colored paint coats are proposed.

1. Introduction
One of the most dangerous types of corrosion damage is under-paint corrosion, since in the early stages of its development, metal corrosion products do not reach the surface of the coating and are hardly noticeable via visual detection. Under-paint corrosion manifests itself in the form of local swelling of the paint coat or in the form of a web that grows rapidly from the epicenter of corrosion. Strands of Under-paint corrosion do not cause severe pitting of the metal, but in the epicenter, the pitting becomes deep, which leads to complete penetration.

In order to obtain objective information about the corrosion phenomena, an inspection by methods of destructive and non-destructive testing is carried out. The methods of destructive control are usually applied after the failure of the technical system. In cases when it is necessary to determine the condition of the control object and the possibility of its further operation, methods of non-destructive testing are used, in particular: ultrasonic flaw detection, acoustic emission, radiography, thermography, the electrical resistance method, etc.

The intensity of corrosion damage is generally determined on the basis of a comparison of the measured thickness of the structural elements with its original dimensions. Thickness measurement is carried out using ultrasonic, magnetic and eddy current thickness gauges. The disadvantages of these methods are the complexity of the measurement due to the curvature and surface roughness, the presence of protective coatings, corrosion products, pollution, etc., as well as the complexity of the corrosion level evaluation process. Evaluation of the intensity of corrosion damage allows for the determination of effectiveness of anti-corrosion measures and the lifetime of the test object [1-4].

Currently, the problem of non-destructive testing of parts using infrared thermography has received much attention. This is due to the relative simplicity, high information content and performance [5], as well as the safety of this method. However, the use of an active method of thermal control for metals
with high thermal diffusivity is associated with a number of problems, one of which is the short lifetime of temperature signals in corrosion zones, which requires the use of additional tools that increase the temperature signal and the time of its optimal observation [6-9]. In addition, a number of monitored parameters cannot be exposed to excessive local temperature effects, sufficient for the emergence of a stable diagnostic signal in order to prevent the occurrence of thermal stresses and to ensure safety.

Considerable difficulties in the implementation of infrared thermography for metal objects are attributed to the high reflectivity of their surfaces. However, the method of active infrared thermography, when recognizing corrosion defects, can be implemented not only on the basis of the difference in thermal and physical properties, but also on the basis of the difference in absorption and reflection coefficients of infrared radiation by the defective and defect-free structures.

2. Experimental program

Studies of surface corrosion of unpainted metals (Fig. 1, b) use of a thermal imager showed that corrosion defects are clearly distinguishable in the obtained thermograms (Fig. 1, a). At the same time, the sample is not exposed to excessive thermal effects necessary to detect hidden defects. The diagnostic signal indicating the presence of a corrosion defect is the result of the difference in the reflection coefficient of infrared radiation from damaged and intact areas of the metal surface.

2.1. Materials

In order to determine the dependence of the diagnostic signal value, indicating the presence of Under-paint corrosion, on the thickness of the paint coating and its color, steel samples of the St3ps GOST 380-2005 grade with detected surface corrosion were prepared, their surface area and location was determined. Next, the samples were coated with acrylic paint of different thickness: sample №1 - the thickness of the paint coating \( h = 9-10 \mu m \); sample № 2 - the thickness of the paint coating \( h = 14-16 \mu m \); sample № 3 - the thickness of the paint coating \( h = 23-25 \mu m \).

To determine the dependence of the diagnostic signal value on the paint coating color, samples with paint coating thickness equal to \( h = 23-25 \mu m \) of different reflectivity of the following colors were prepared: sample № 4 - gloss black (paint brand Otrix number 926); sample № 5 - matte black (paint brand Kudo KU-1102); sample № 6 - gloss white (paint brand Otrix number 927); sample № 7 - matte white (Red Fox paint № 1007 (F100)); sample № 8 - gloss red (paint brand Mobihel Helios № 1015); sample № 9 - metallic colors (paint brand Parade R-3012).

2.2. Experimental methods

Samples were exposed to an infrared source. The testing was carried out using a Testo-875-1i thermal imager, equipped with a 160x120 pixel matrix with high temperature sensitivity (NETD) <50 mK which allowed to obtain thermograms with a resolution of 320x240. The measurements were carried out in accordance with a one-way procedure.

Figure 1. Thermal imaging of a sample which was subject to corrosion: a) thermogram of the reflection of infrared radiation from the sample surface; b) regular image of the sample which was subject to corrosion.
When determining the dependence of the diagnostic signal value on the thickness of the paint coating, the samples were subjected to a short-term (τ = 0.5 min.) exposure to infrared radiation. According to the measurement results, thermograms were obtained and histograms of the reflected temperature distribution were constructed (Fig. 2-4).

![Figure 2](image1.png)

**Figure 2.** Measurement results of sample № 1: a) thermogram of the reflected temperature distribution; b) a histogram of the temperature distribution on the surface of samples in the areas selected for analysis.

![Figure 3](image2.png)

**Figure 3.** Measurement results of sample № 2: a) thermogram of the reflected temperature distribution; b) a histogram of the temperature distribution on the surface of samples in the areas selected for analysis.

![Figure 4](image3.png)

**Figure 4.** Measurement results of sample № 3: a) thermogram of the reflected temperature distribution; b) a histogram of the temperature distribution on the surface of samples in the areas selected for analysis.
3. Results and discussing

Analysis of the obtained thermograms of samples № 1-3 showed that the thickness of the paint coating practically does not affect the value of the diagnostic signal, and the temperature range corresponding to the Under-paint corrosion defect is in the range from 26.2 - 28.5°C with a temperature of the defect-free surface of about 30°C. The temperature of the samples after the completion of studies on the detection of Under-paint corrosion, with dependence on the thickness of the paint coating, averaged 24.4 - 25°C.

The automatic generation of histograms of temperature distribution on the surface of samples using a special software application called Testo allows to obtain a quantitative estimate of corrosion damage level: for sample № 1 - 52.9% (Fig. 2, b); for sample №2 - 48.4% (Fig. 3, b); for sample № 3 - 30.2% (Fig. 4, b).

Unlike the thickness, the color of paint coating has a significant impact on the value of the diagnostic signal.

As a result of the measurements, thermograms were obtained showing the distribution of the reflected heat flow from the defective structure of the sample (Fig. 5).

The obtained thermograms (Fig. 5) clearly show the temperature diagnostic signals that indicate the presence of corrosion centers (pinpoint corrosion damage). Corrosion damage has a lower reflected temperature compared with a defect-free surface. This difference is explained by the fact that the reflectivity of a defect-free (relatively smooth) surface is higher than that of a surface with corrosion damage (deviation of the surface micro-profile).

As a result of the analysis of the obtained thermograms, made with the help of a special software application called Testo, the average values of the reflected temperatures from the surfaces of samples with paint coatings of various colors (Table 1) were determined.

| Paint coating color | The average reflected temperature from the defect-free surface, °C | The average reflected temperature from corrosion damaged surfaces, °C | Average surface temperature of the infrared source, °C |
|---------------------|---------------------------------------------------------------|---------------------------------------------------------------|-----------------------------------------------|
| matte white         | 44,20                                                         | 43,40                                                         | 117,90                                        |
| gloss white         | 45,90                                                         | 44,30                                                         | 117,80                                        |
| gloss red           | 49,85                                                         | 47,50                                                         | 117,20                                        |
| matte black         | 59,40                                                         | 56,76                                                         | 120,50                                        |
| gloss black         | 56,40                                                         | 54,37                                                         | 115,10                                        |
| metallic            | 79,90                                                         | 70,55                                                         | 114,80                                        |

When processing the results of experimental studies, it is necessary to minimize (eliminate) the likelihood of an error due to the presence of inconsistencies, which are differences in ambient temperature and the temperature of the source of infrared radiation at different stages of measurement. The values of the reflected heat flow from the defective and defect-free structures are presented as a coefficient of reflection. The average reflection temperature \(<t_{ref}>\) divided by the average temperature of the infrared source \(<t_s>\) equals to the coefficient of reflection \(K_{ref}\).

\[
K_{ref} = \left(\frac{t_{ref}}{t_s}\right) .
\] (1)

The higher value of the reflection coefficient of black surfaces compared to white surfaces (Table 2) is explained by the fact that white surfaces reflect visible light rays well and almost completely absorb infrared rays.
Figure 5. Thermograms of the distribution of the reflected heat flow from samples with different colors of paint coatings: a) matte white; b) gloss white; c) matte black; d) gloss black; e) metallic; f) gloss red.

Since the corrosion damage is local, that is, in the area of interest of the surface of the test object, there is a point diagnostic signal indicating the presence of a defect, simultaneously with the signal from the defect-free structure, it is possible to diagnose corrosion damage by the value of indicator $\delta$, expressed as a ratio between $K_{ref}^{dem}$ and $K_{ref}$:

$$\delta = 100 - \frac{K_{ref}^{dem}}{K_{ref}}$$  \hspace{1cm} (2)

Table 2. Change in the reflection coefficient of the heat flow depending on the color of the paint coating

| Paint coating color | The reflection coefficient of the heat flow from the defect-free surface, $K_{ref}$ | The reflection coefficient of the heat flow from the defective surface, $K_{ref}^{dem}$ | $\delta$, % |
|---------------------|------------------------------------------|------------------------------------------|-----------|
| matte white         | 0,375                                    | 0,368                                    | 1,9       |
| gloss white         | 0,390                                    | 0,376                                    | 3,6       |
| gloss red           | 0,425                                    | 0,400                                    | 5,9       |
| matte black         | 0,484                                    | 0,470                                    | 2,9       |
| gloss black         | 0,490                                    | 0,472                                    | 3,7       |
| metallic            | 0,69                                     | 0,615                                    | 10,9      |
Indicator $\delta$ for each sample has its value depending on the color. As can be seen from the table 2, the smallest value of $\delta$ corresponds to a sample with a matte white paint coating, and the largest value corresponds to a metallic color sample, which is explained by the different reflectivity of different colors.

Figure 6 shows software application plotted distribution of the reflected heat flow in the Under-paint corrosion area (the area between ABCDE points), from which it can be seen that the presence of a defect is characterized by an abrupt change in temperature $T = 27.4 \, ^\circ\text{C}$ (point C), the average temperature of the defect-free region is $T = 29\, ^\circ\text{C}$. From the graph (Fig. 6) it is also possible to determine the geometrical dimensions of the corrosion defect, which for this example are $L = 2$ mm (the distance between points A and E).

Thus, the evaluation of the intensity of under-paint corrosion growth over time can be done using the mathematical apparatus of the catastrophe theory. If the system is controlled by two parameters, then only two types of disasters are possible: «crease» and «assembly».

To estimate the coefficient which indicates the degree of metal damage from corrosion $Y$, the authors [10-11] propose to use the «crease» type catastrophe equation:

$$Y(x, a) = \frac{x^3}{3} + ax,$$  \hspace{1cm} (3)

where $x$ and $a$ are numerical factors that indicate the state of the system: $x$ is the coefficient which indicates the dimensions of the corrosion defect (in longitudinal and / or cross section), and $a$ is the coefficient which indicates the positive growth rate (or negative growth rate (for example, at negative temperatures)) of the corrosion defect.

![Figure 6](image)

**Figure 6.** The graph of the distribution of the reflected heat flux (reflected temperature) from the surface of the sample with a diagnostic signal at point C - the bifurcation point.

This equation allows us to obtain a quantitative estimate of the output parameter $Y$.

Numerical determination of the coefficients which indicate the size of corrosion damage (in longitudinal and / or cross section) $x$, and the coefficients which indicate the positive (or negative) growth rate of corrosion damage $a$, is a very difficult and in many cases unsolvable problem. As an example of a fold-type catastrophe, we consider how the state of the system will change when the coefficients $a$ and $x$ change step by step. The range of values of the coefficient $a$ is set from -100 to +100 with a step of 20, and the coefficient $x$ from 1 to 18 with a step of 3.
In table 3, the darker areas denote of the desired value Y, which indicate its slow change, while in the range from \( x = 15 \) to \( x = 18 \) there is a sharp abrupt change in Y with a change of sign, showing that a threshold effect is being overcome, at which the system undergoes total destruction. In this case a leap-approach occurs at several points. For example, for values \( a = -100 \), these are two points at \( x = 15 \) and \( x = 18 \). At the first point (at \( x = 15 \) and \( a = -100 \), the first local minimum occurs. At the second point (at \( x = 18 \) and \( a = -100 \), the second local minimum occurs, and this critical point is the bifurcation point for this example. Similar points of local minimums occur when the values of \( a = -20 \) are \( x = 6 \) and \( x = 9 \).

Therefore, the use of infrared thermography, based on the registration of the reflected heat flow from the surface of the control object, allows for a qualitative and quantitative evaluation of the degree of corrosion of machine parts and specialized equipment without exposing the control objects to excessive temperatures. The presented method is safe, requires low labor intensity, is highly informative and does not require the involvement of highly qualified specialists.

Based on the evaluation of the degree of corrosion damage of the control object, a decision can be made on the economic feasibility of eliminating corrosion defects or replacing structural elements of automobile bodies with new parts. The accumulation of data on the corrosion level of the test object allows for the prediction of its remaining service life, as well as for the development of measures to prevent further occurrences of corrosion defects.

### Table 3. Change of the output parameter which indicates the loss of performance of the metal structure

| \( a \) | \( x \) | 1  | 3  | 6  | 9  | 12 | 15 | 18 |
|--------|------|----|----|----|----|----|----|----|
| -100   | -99,67 | -291 | -528 | -657 | -624 | -375 | 144 |
| -80    | -79,67 | -231 | -408 | -477 | -384 | -75  | 504 |
| -60    | -59,67 | -171 | -288 | -297 | -144 | 225  | 864 |
| -40    | -39,67 | -111 | -168 | -117 | 96   | 525  | 1224 |
| -20    | -19,67 | -51  | -48  | 63   | 336  | 825  | 1584 |
| 0      | 0,33   | 9    | 72   | 243  | 576  | 1125 | 1944 |
| 20     | 20,33  | 69   | 192  | 423  | 816  | 1425 | 2304 |
| 40     | 40,33  | 129  | 312  | 603  | 1056 | 1725 | 2664 |
| 60     | 60,33  | 189  | 432  | 783  | 1296 | 2025 | 3024 |
| 80     | 80,33  | 249  | 552  | 963  | 1536 | 2325 | 3384 |
| 100    | 100,33 | 309  | 672  | 1143 | 1776 | 2625 | 3744 |

The use of the equations of the catastrophe theory in evaluating the degree of metal damage by corrosion allows us to determine the maximum permissible dimensions of a corrosion defect at a given intensity of its growth.

### 4. Conclusion

The values of temperature diagnostic signals from corrosion damage corresponding to the specific colors of the paint coating of automobile bodies obtained in the process of experimental studies, make it possible to avoid errors of «false alarm» diagnostics and the associated costs of wrongly replacing parts. Also, when diagnosing surfaces of automobile bodies using a method based on recording and comparing reflected heat flows from corrosion-damaged and defect-free structures, there is a risk of a «false alarm» due to the presence of residues of contamination and / or moisture on the test surface, as
well as the formation of glare from items that can be mistaken for corrosive defects in the subsequent analysis of the obtained thermograms [11].

Analyzing the values of $\delta$, we can conclude that the proposed evaluation method of the degree of corrosion damage for objects with a matte white acrylic coating is less effective than for samples with paint coating of other colors. For objects with matte white acrylic paint coating, it is advisable to apply alternative physical methods of non-destructive testing (for example, ultrasonic defect detection).

Due to the difference in physical and chemical properties of various types of paint coating materials (alkyd, polyurethane, epoxy, etc.), the research results obtained during the application of the described method can be used only to evaluate the degree of corrosion damage to objects with acrylic paint coating materials. Conducting additional research to determine the possibilities of detecting under-paint corrosion in objects with different types of paint coating materials will lead to the development of more comprehensive recommendations and will expand the scope of this method.

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