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# ТЕРМОГРАФСКО РАЗПОЗНАВАНЕ НА СКРИТА КОРОЗИЯ

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# HIDDEN CORROSION RECOGNITION BY THERMOGRAPHY

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***Abstract:****Detecting and evaluating hidden corrosion remains a challenging task in many vital industrial areas. Infrared thermography (IRT) is a remote and fast diagnostic tool. Thanks to the rapid development of electronic devices and the new construction of equipment, thermography has become more popular. There are new applications for this technology for corrosion recognition in engineering and the army. An approach of IRT technique is discussed that eliminates the need for prior knowledge of a corrosion free area to allow automatic identification of corrosion areas from thermograms. This technique can be utilized in both static and active nondestructive (NDE) IRT modes. The paper presents the comparison of the results obtained by experimental measurements*

***Key words****: thermography, non-destructive evaluation, corrosion, defect selective imaging*

## Introduction

Corrosion is one major factor that defines the maintenance cost high and is cause for premature failures. Determining early signs of corrosion and corrosion-assisted damage is essential to corrosion prevention, life prediction and helps cut down major repairs and catastrophic losses. The corrosion is a wide problem that has been rapidly spreading due to the increased amount of infrastructure and military assets that are aging. Even in the case of newer systems and components, corrosion can be a significant problem because of the harsh operational environments encountered. Recognition of the severity and the economic impact of the corrosion problem by various industries have led to significant effort to prevent and control corrosion. Nondestructive evaluation (NDE) plays an important role in this effort by enabling the detection of early signs of corrosion so that corrective action can be taken before the damage becomes severe.

Hidden corrosion is a type of electrochemical material degradation that is not readily detectable visually or by any other surface measurement technique [1]. It can often be detected and quantified in terms of reduction of wall thickness or structural discontinuities such as pits, flaws and voids. When attempting to detect material degradation due to electrochemical processes, the corrosion products (for example, iron oxides, aluminum oxides, etc.) must be identified.

Nondestructive evaluation (NDE) of corrosion is typically conducted by applying enhanced visual/optical techniques, as well as using ultrasonic, eddy current, radiographic and thermographic inspection. There are two main application areas for NDE methods: detection of corrosion damage and detection of hidden corrosion.

Infrared thermography (IRT) is based on the principle that a good mechanical bond between two materials is also a good thermal bond. The temperature distribution on a component can be measured optically by the radiation that it produces at infrared wavelengths. Several techniques have been developed that use this temperature information to characterize the thermal – and therefore the structural - properties of the sample being tested.

The corrosion thermal detection theory is based on solving a differential equation of transient heat conduction in solids. In general case of small-size defects, this equation should be three-dimensional (3D) that typically requires using numerical methods.

Recovering the desired corrosion data is a mathematical inversion problem. Depending on the energy source used, the characteristics of materials and the corrosion hidden in structural systems, an exact solution of the inversion problem may not be feasible. Therefore, data analysis and information processing, such as the use of neural networks, wavelet analysis, target segmentation, fuzzy logic, statistical analysis , etc. have become key enablers in developing NDE techniques for hidden corrosion.

Corrosion may appear in various forms (galvanic, crevice, intergranular and erosion corrosion, pitting, hydrogen induced environmental and stress corrosion cracking) depending on the alloy, product form, corrodent, general conditions and residual stress [4]. This complicates the metrics of corrosion and therefore also complicates the quantification of detection reliability.

In this study, we summarize principle features and results of using IRT in corrosion detection, in different areas.

## IRT inspection modes

Based on how the thermogram is produced, there are two types of IRT: active and passive thermography. In active thermography, an external heat source is applied when capturing thermogram. In a normal condition, the temperature gradient between the defective and nondefective (sound) area is undistinguishable. Immediately after applying the heat source, the infrared thermal camera can record the difference between these two areas. In passive thermography, no external heat source is applied when capturing the thermogram since the temperature difference between defective and sound area is so obvious already. Figure 1 shows configuration for these two modes of IRT.

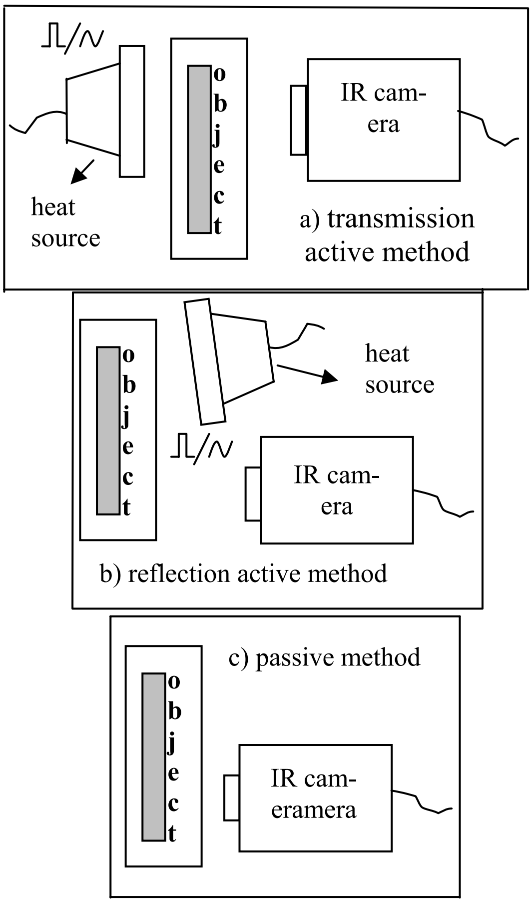


*Fig.1. IRT modes: a) and b) active; c) passive thermography*

Heat deposition can be done by a pulse (e.g. flash lamps) or by modulation (e.g. halogen lamps, laser) or by step stress (e.g. infrared or quartz lamps). The simplest way of evaluation is to record a temperature image sequence after heating and to evaluate the image sequences.

Corrosion is detected and recognized by analyzing spatial–temporal phenomena which occur in corroded sites subject to stimulated heating. The heat flux delivered onto a sample surface by an external or internal source propagates in-depth and goes through specific disturbances in corroded areas. Peculiarities of such detection technique were discussed in [5, 6] from the point of view of non-destructive testing (NDT). Very few studies were devoted to analyzing relationship between different types of corrosion and corresponding surface temperature patterns [7].

**Data analysis**

Traditional image analysis routines are not suitable for processing the acquired thermal images or thermograms, because of the heating non-uniformities, which could be a result of the high tolerances in corrosion depth, profile and geometry. All of this creates non-uniform thermal maps. To provide a complete automated detection package, image processing software (ENVI software was used in the project) is required to isolate the corroded areas from their surroundings.

The relative material loss (i.e. the ratio between the residual thickness in the corroded spot and the thickness of the defect-free area) is a function of the temperatures over the defect (corrosive area) and the non-defect (sound) area.

The goal is to study the deviation in the logarithmic temperature time history slope. This technique is based on comparing the behavior of a defective pixel with kernel (21x21) pixels surrounding [7]. To maximize the accuracy of defect detection, the size of the local neighborhood should be selected such that it will be larger than the defect and sizes sought and assure a stable temperature across the region, but small enough to be contained within the smallest area of non-uniformity. The principle of this technique is to divide the thermogram image into small local neighborhoods to serve as the non-defective behavior required for the thermal contrast computation. The contrast will be computed through the following equation:

(1) $$C(i,j,t) = T_k(i,j,t) - T_{s_k}(t)$$

where $T_k$ $(i,j,t)$ is the temperature of the k-$^{th}$ pixel at i, j coordinates and time t , $Ts_k(t)$ is the average temperature of the neighborhood surrounding the pixel (i, j) at time t .

In contrast to [7] in the work was also used the median of the surrounding neighborhood temperatures rather than the average.

The size of the local neighborhood should be selected such that it will be larger than the corrosive and sizes sought and assure a stable temperature across the region, but small enough to be contained within the smallest area of non-uniformity (its definition dependant on the application at hand). A relative thresholding step follows, where each pixel in the thermal image is compared against the median of its surrounding neighborhood; if it passes the criterion in (1), its value is boosted with multiples of the difference from the median otherwise its value is set to zero.

(2) $$|T_k - T_m| \geq A\sigma_{s_k}$$

where $T_k$ is the temperature of central pixel, $T_m$ is the kernel median temperature, $A$ is a scaling factor dependant on the signal to noise ratio of the thermogram, and $\sigma_{sk}$ is the standard deviation of pixels in the local neighborhood surrounding.

The result of the procedure is shown in fig. 2.

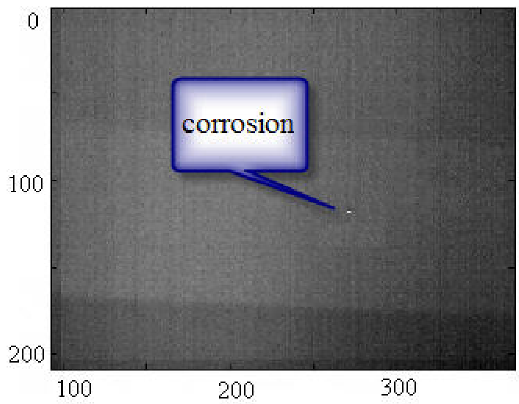


*Fig.2 Computed contrast*

Applying a thersholding step according to equation (2) criterion the result on fig.3 shows the effectiveness of such approach in isolating the features of interest from the rest. A profile of intensity values is drawn on fig.4 to show the contrast obtained with this technique.

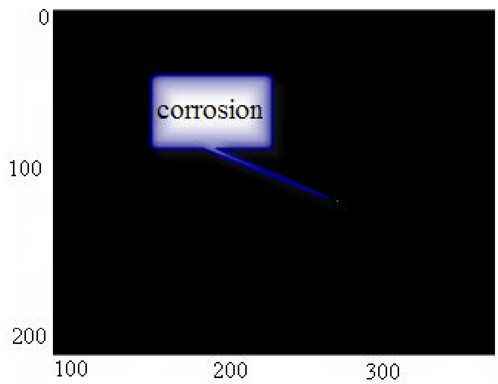


*Fig. 3. Thresholded thermogram.*

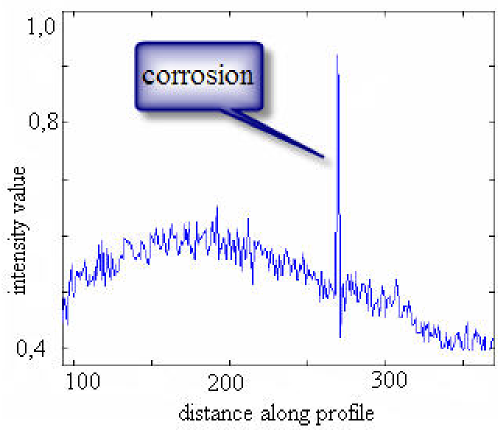


*Fig.4. Intensity profile*

On fig.5 are shown the original thermogram and processed image of hidden corrosion on metallic pipe.

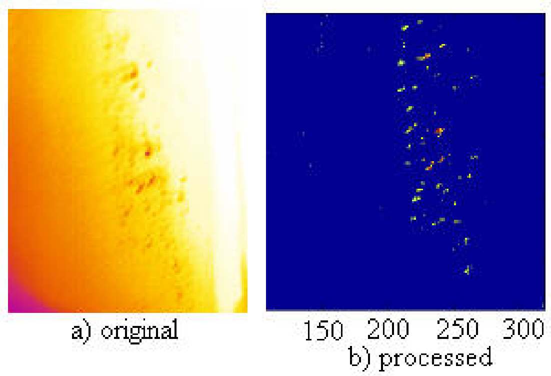


*Fig.5. The original thermogram –a) and corresponding processed thermogram-b) of a sample wit corrosion in the form of pinhole*

To quantify the code performance, the next criterion can be used:

$$r = \frac{n_r - n_m}{n_r - n_f} \qquad (3)$$

where, $n$ is the number of defects and the subscripts $r$ ,$m$ , $f$ refer to real defects (from corrosion), missed defects and false positives found in the processed image.

This criterion to the processed images results in average of r = 95 %. Applying the criterion for a single image with limited number of defectives is considered highly conservative, and so any r > 80% indicates effective processing.

A computer algorithm using ENVI software was prepared to perform the infrared thermographic procedures for the sequence of thermograms obtained from the developed computation scheme.

The thermographic data can be represented as a thickness map for the area under inspection. This map represents all of the data in single image. The depth in every one pixel is given by:

$$d(i,j) = pC_{\max}(i,j)^q \sqrt{t_{\max}(i,j)} \qquad (4)$$

where $d(i, j)$ is the depth at location $(i, j)$ , $p$ and $q$ are constants determined experimentally (dependant on the material under inspection), $t_{max}$ $(i, j)$ is the time at position $(i, j)$ taken from the timegram matrix, $C_{max}$ $(i, j)$ is the contrast value at $(i, j)$ from the contrast matrix.

The result of the NDT IRT procedure is shown on fig. 6, which shows corrosion areas in the middle of the tested metallic sample.

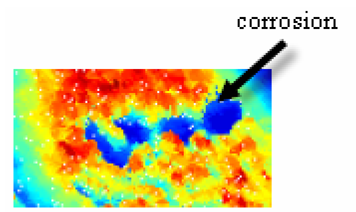


*Fig.6 Reconstructed thickness map of a metallic sample*

## Equipment and application of IR corrosion inspection

During the experimental studies an infrared camera model FLIR ThermaCam SC640, completed with a set of lenses, SDK, PC, ENVI and ThermaCam Researcher software were used. For active NDT IRT experiments were used Flash. Quartz and halogen sets of lamps with different power.

The corrosion degree estimation may be performed by using one of the inverse methods [8]. The simplest algorithm connects the relative material loss and the instantaneous contrast through the equation:

$$\frac{\Delta L}{L} = \frac{C(i,j,\tau_\infty)}{1 + C(i,j,\tau_\infty)} \qquad (4)$$

where $C(i, j, \tau_\infty)$ is the contrast of a stationary condition.

The time interval during which the temperature response at the material surface is observed is most frequently expressed nondimensionally, i.e. using the Fourier number:

$$F_0 = \frac{\alpha\tau}{L^2} \tag{5}$$

where $\alpha$ – thermal diffusivity of the material, ($m^2/s$), $\tau$ - time interval, (s), and $L$ – thickness of the plate, (m).

For large defects the heat transport may be reduced to a one-dimensional problem. The optimal inspection time is in the range Fo ≈ 0,6 ÷ 2,0, and equation (4) is recommended. The characterization of smaller defects of complex shape is recommended in the interval Fo ≈ 0,3 ÷ 0,6 [8].

An experimental procedure of corrosion detection involves identifying a suspicious area by the operator, then placing a reference point and, finally, estimating corrosion by equation (8).

Inspection of corrosion in aluminum aircraft panels and aboveground steel tanks are the two main areas of application of active IR thermography. Depending on the used IR camera's lenses it can be covered areas from a sample from about 10 $cm^2$ to 100 $m^2$. A typical flash duration between 3 and 10 ms enables an accepted time resolution even in the inspection of thin aluminum. The inspection of steel samples of up to 15 mm thickness is not a problem. But thick steel samples require a large amount of absorbed energy that is hard to realize with available flash tubes.

Therefore, in this case, flash tubes should be replaced with quartz bulbs which allow smooth controlling of both power and pulse duration.

The demand for miniaturization, multiplicity of materials used, etc. has opened up serious corrosion problems in consumer electronics [9]. It is a sector where passive IRT could be successfully used for hidden corrosion detection.

## Conclusions

A statistical detection limit can be of about few percent by material loss. In case of steel structures of 5-15 mm thickness, a heating pulse should be optimized by energy and pulse duration to ensure a reasonable temperature elevation. A detection limit in this case is estimated as about 20 % by material loss with the detection limit being put by stimulation energy.

A quality approach to thermal non-destructive testing necessarily requests a close collaboration of experiment and numerical analysis in order to detect and determine all the relevant defect parameters.

A real detection limit is put by surface noise (rust, dust, paint, scratch etc.). Even on black painted surfaces, the minimum noise is about 2 % and the detection limit is ~2 %. If a typical signal-to-noise ratio is about 3, the practical corrosion detection limit is about 5-6 % by material loss.

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