Pulse laser thermography as a non-destructive method of latent surface defects of materials

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Abstract. The time dependences of the surface temperature increment of painted metal objects were studied depending on the thickness of the layer subjected to corrosion, as well as putty, restoring erosion defects on it. Hidden under a layer of paint, they cannot be detected remotely during normal visual observation. At the same time they are well detected by pulsed laser thermography. The experimental data in the work are compared with the results of mathematical modeling. Particular attention is paid to eliminating possible distortions caused by external contamination of the tested objects.

1. Introduction
Remote detection of latent defects on the surface of materials based on active photothermal radiometry (thermography) is a very attractive technology, the beginning of which was laid in the late 70s - early 80s of the last century [1 - 4]. Over the years, this technology has undergone significant development. In the broad sense of the word, one can speak of flash thermography [5, 6] and modulation (lock-in) IR thermography [7, 8]. In this case pulsed, or non-stationary, thermography is the most common form of non-destructive assessment of the object of study using the thermographic method (NDE, nondestructive evaluation) [9 - 13]. This is due to the possibility of studying significant areas on the surface of the object in the presence of a high-speed IR camera with a large field of view, which is of fundamental importance for increasing the productivity of non-destructive testing of materials. Therefore, the main attention in the future will be given to the possibilities and development of this particular type of material research.

The physical principle underlying the use of flash thermography for non-destructive testing is to measure the time dependence of surface temperature changes, while lock-in thermography allows you to study the phase of the photothermal signal. In both cases, the difference in thermal diffusion in different places of the sample due to the presence of defects and inhomogeneities in it affects the measurement result. In other words, subsurface defects change the rate of thermal diffusion, thereby manifesting itself in a change in the parameters of the recorded photothermal signal in the places where defects exist relative to areas where they are absent. Any inhomogeneities, such as inclusions, subsurface defects, or porous formations distort the propagation of thermal waves and modify the temperature response on the surface of the sample in comparison with the defect-free region. Due to the direct relationship between the thermal and mechanical properties, the detection of the distribution of the thermal signal allows mapping of the physical properties of the material under study during its scanning.
The development of flash thermography and lock-in thermography methods is pulse phase thermography based on the application of the Fourier transform to the function of temperature change over time [14, 15]. Pulse phase thermography maximally implements the idea of taking into account the fundamental differences in temperature evolution in defective and defect-free (reference) areas of the test object. However, its implementation in practice requires considerable time, since one has to deal with sequences consisting of several hundred and even thousands of images.

In the classic active pulsed thermographic technique (flash thermography), the studied surface of the object is heated under the influence of radiation from one or several flash lamps, after which its cooling is recorded using an IR camera. This method has long been used for non-destructive and non-contact investigation of interfaces between the surface layer (coating) and the base material (substrate), for example, to detect adhesion defects (delaminations), local corrosion foci, surface cracks that change the one-dimensional heat flux from the surface [13].

However, a significant divergence of radiation from flash lamps and its low spectral brightness significantly limit the scope of flash thermography, in particular, when testing objects located at a considerable distance from the heating source. At the same time, just such a task is currently gaining more urgency and attention of researchers, since it is related to remote monitoring of structures, for example, in the form of bridges, tanks for transporting and storing petroleum products, liquefied gas, car bodies, building walls and etc.

The aim of this work is to demonstrate a new approach for remote monitoring of the surface condition of various structures located at considerable distances from the heating source using pulsed laser thermography, which excludes the influence of external factors (for example, contamination of the object's surface) on the detection of "camouflaged" subsurface defects. The solution to this problem became possible in connection with the creation of powerful and at the same time compact semiconductor lasers emitting at different wavelengths of the electromagnetic spectrum (from UV to far IR).

2. **Experimental setup**

Fig.1 shows an experimental setup for remote analysis of the surface of materials by means of pulsed laser thermography.

The studied sample (1) is affected by laser radiation pulses (2) formed by an electromechanical chopper (3).

![Figure 1.](image)

**Figure 1.** a) Scheme of non-destructive testing of hidden subsurface defects using laser pulse thermography; b) Photo of the experimental setup.

1 — sample, 2 — laser, 3 — radiation chopper, 4 — infrared camera, 5 — control panel, 6 — monitor, 7 — computer, 8 — hidden subsurface defect, 9 — protective coating (paint)
The source of laser radiation in the work was the assembly of semiconductor laser diodes (average radiation power 90 W) with a generation wavelength of 915 nm, having a common optical fiber output. The duration of laser exposure was set by a timer from the control panel (5), which was connected electrically with a laser chopper. An IR camera (4) was used to register a map of local temperature increments on the surface of the test sample. Thermographic images were presented on a monitor screen (6) and could be adjusted using a special computer program (7).

The laser exposure area and the corresponding power of laser radiation density could be changed using a tunable lens.

Samples in the form of bars of structural steel of the St3 grade with surface defects (8) under a dark protective coating layer (9) were used as a target. At the same time, the areas exposed to corrosion on the surface of the test areas did not appear in any way when remotely observing samples using a visible range CCD camera or a thermal imaging camera in the absence of laser radiation. As an infrared camera, FLIR Tau2 with a resolution of 336 × 256 with a pixel size of 17 μm and a sensitivity of 0.05 mK was used.

3. Thermographic results

When a sample is irradiated with laser radiation, latent defects in the form of rust-affected areas are clearly visible when observed using an infrared camera located at a distance of 10 m associated with a laser system (Fig. 2). The same figure shows the result of visualization of a hidden defect under similar conditions in the form of cross-shaped surface cracks 2 mm deep, obtained by means of spark erosion, coated with polyester putty, followed by polishing and painting the surface with alkyd enamel. Such masking of surface cracks also made it impossible to visualize them in the visible range of the spectrum even at high magnification, as well as when observed with a thermal imager. However hidden defects of this kind can be visualized using pulsed laser thermography (Fig. 2b).

![Thermographic images observed after laser irradiation of a metal plate with local defects under a layer of paint: (a) iron corrosion centers, (b) cross-shaped surface cracks](image)

Figure 2. Thermographic images observed after laser irradiation of a metal plate with local defects under a layer of paint: (a) iron corrosion centers, (b) cross-shaped surface cracks

In the above figures a thermal footprint is clearly visible due to a violation of the heat sink in the defective area of the test sample, hidden by a protective coating. In this case, the paint coating absorbed at least 80% of the radiation energy, the emissivity in the region of 7.5 - 13 μm was 0.9.

Fig.3 shows the time dependences of the increment in the surface temperature of the sample depending on the thickness of the layer subjected to corrosion (Fig. 3a) and the thickness of the protective layer hiding cross-shaped traces of erosion (Fig. 3b).

These dependencies can be used as the basis for quantitative estimates of the parameters of latent surface defects in materials.

Under real conditions, the detection of hidden near-surface defects by pulsed laser thermography can distort the presence of a number of factors. In particular, external surface contamination can give...
an ambiguous interpretation in the infrared region. The presence on the surface of areas with increased absorption of laser radiation leads to their overheating in comparison with the rest of the sample. On the other hand, the presence of stains of a foreign substance can be accompanied by a local change in the emissivity of the surface. In both cases, testing the object by means of laser thermography gives a picture of heterogeneity, which can hide the presence of defects under the surface or distort their nature.

![Figure 3](image_url)

**Figure 3.** Time dependences of changes in the surface temperature of plates made of St3 steel when exposed to laser radiation with a power density of 0.4 W/cm$^2$ for 33 seconds and subsequent cooling for different thicknesses $h$ of the surface layers of (a) corrosion products of hydrated iron oxide: 1- $h = 0.25$ mm, 2- $h = 0.5$ mm, 3- $h = 0.8$ mm, 4- $h = 1.1$ mm, 5- $h = 2.3$ mm; (b) polyester putty: 1- $h = 0.25$ mm, 2- $h = 0.5$ mm, 3- $h = 1.6$ mm, 4- $h = 2.5$ mm

It is possible to eliminate false responses by comparing the images of the thermal imager with the corresponding images of the visible range camera, on which obvious surface contamination is usually clearly observed. And only when a homogeneous picture is recorded in the latter case, we can talk about the possibility of detecting latent defects using laser thermography. Unfortunately, it is not always possible to clean the surface from contamination, especially for remote objects located in hard-to-reach places.

In addition, the above experimental results do not allow us to unequivocally state that there is a corrosion defect at the interface. At the same time, another approach is possible to solve the problem associated with filtering false test results. In this case it can be assumed that the shape of these thermal radiation pulses is a determining factor in the procedure for detecting and recognizing latent defects. A computer program for analyzing thermographic images made it possible to correct external contaminants, taking into account the analysis technique for cooling the irradiated surface described in the next section.

4. Computer simulation of thermal processes

The simulation of the results of laser irradiation was carried out on samples of a simplified composition: with a massive base of heat-conducting material (metal) and a surface layer with low heat conductivity (polymer) of various thicknesses, which imitated a surface defect. It is believed that all objects are covered with a thin film of the same protective paint to ensure equal absorption coefficients of laser radiation and emissivity in the spectral range of the recorded thermal signal. As model objects, samples from steel bars with a thickness of $H = 60$ mm with plastic layers of various thicknesses $h$ were considered.

Laser heating is modeled by the one-dimensional equation of heat conduction along the $x$ axis written for two contacting materials with thicknesses $h, H$ and thermal diffusivity coefficients
\( \alpha_1 = 1.5 \times 10^{-7} \text{ m}^2/\text{s} \) and \( \alpha_2 = 1.3 \times 10^{-5} \text{ m}^2/\text{s} \), respectively.

At the initial time, the temperature of the sample is uniform and equal to \( T_0 \). The condition at the interface: \( T_1(h) = T_2(h) \), on the surface: \( T(h + H) = T_0 \).

The problem described by the system of equations must be solved:

\[
\begin{align*}
\frac{\partial T}{\partial t} &= \alpha_1 \frac{\partial^2 T}{\partial x^2}, \\ 0 < x < h \\
\frac{\partial T}{\partial t} &= \alpha_2 \frac{\partial^2 T}{\partial x^2}, \\ h < x < h + H
\end{align*}
\]

(1)

Numerical simulation of the problem was carried out using finite-difference analysis. Fig. 4a shows the graphs of the obtained time dependence of the surface temperature \( T_{\text{norm}} \) of a number of samples on the dimensionless parameter \( k = t/\tau \) (\( \tau \) is the duration of the pulse exposure) in a normalized form.

**Figure 4a.** The calculated time dependences of the relative surface temperatures of the layered structure for different values of \( h \). The data are presented in dimensionless coordinates \( k = t/\tau \) for a laser pulse duration of \( \tau = 20 \text{ sec} \): 1 – \( h = 0 \); 2 – \( h = 0.2 \text{ mm} \); 3 – \( h = 0.5 \text{ mm} \); 4 – \( h = 1.1 \text{ mm} \).

**Figure 4b.** Dependences of the integrals of normalized temperatures on the thickness \( h \) of the surface layer of polymer: 1 - integral from \( k = 0 \) to \( k = 1 \) (heating during a laser pulse), 2 - integral from \( k = 1 \) to \( k = 5 \) (cooling)

Figure 4b shows the dependences of the normalized temperature integrals on the thickness \( h \) of the surface layer for the heating process (curve 1) and cooling (curve 2). It can be seen that the dependence of the quantity under consideration on \( h \) is weak and ambiguous in the region of action of the laser pulse. But when the object cools down, analysis of the integral of the thermal signal can give an unambiguous answer about the value of \( h \).

An example showing the advantage of the described approach is illustrated by the images shown in Fig. 5.

**Figure 5.** a - surface image in visible light (there is a dark spot on the paint); b – spatial distribution of the thermal signal recorded in pulsed laser thermography of the same sample; c - the result of the analysis of subsurface defects using the described technique.
The general view of the sample in visible light is reflected in Fig. 5a. On the surface of the paint coating there is a stain of contamination, which leads to an increase in local absorption of laser radiation. The corresponding zone of increased heating is manifested in the results of pulsed thermography, based only on a comparative analysis of the amplitude characteristics of the heat signal from various parts of the surface of the investigated object (Fig. 5b). This distorts the expected results of a study of subsurface material defects. At the same time, the use of computer processing of a series of consecutive IR images of a sample after exposure to laser heating in accordance with the method of mathematical modeling described above allows identifying precisely surface defects hidden by polymer putty under a common paint layer (Fig. 5c).

With appropriate calibration it is possible not only to detect but also to identify the nature of latent defects in the surface layer of the material.

5. Summary
A new approach to visualization of a hidden defect has been developed by "extracting" it from a digital image of a distorted thermal field caused by heating of surface contamination. This approach is carried out using pulsed laser thermography by analyzing and processing the attenuation curve of the photothermal signal. It is shown that it is possible to detect corrosion products of hydrated iron oxide with a thickness of 100 microns or less at a distance of 10 m.

An experimental technique for detecting hidden surface defects in materials can satisfy the needs of remote monitoring of metal structures in the form of bridges, ships, tanks for transporting and storing petroleum products, etc.

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