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МЕТРОЛОГІЯ, СТАНДАРТИЗАЦІЯ І СЕРТИФІКАЦІЯ

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A COMPREHENSIVE METHOD OF A DEFECT MAP FORMING BASED ON THERMAL RESPONSE PATTERNS

О. Левинський, Г. Оборський. **Комплексна методика формування карти дефектів на основі паттернів теплового відгуку**. Розглянуто сучасні підходи, що використовуються при аналізі результатів термографічного аналізу тестового об'єкта з метою виділення структурних особливостей з метою формування карти дефектів. Вказано на переваги застосування методів статистичного аналізу термограми з визначенням на кількісному рівні цільового показника сигнал-шум та оптимізацією процедури термографічного аналізу через пошук глобального екстремуму цільової функції. У відповідності до розробленої методики розглядається набір чотирьох результатів, що може бути отримано в результаті проведення термографічного аналізу тестового об'єкта, як то істинно позитивний результат, хибно позитивний результат, істинно негативний результат, хибно негативний результат. Аналіз результатів термографічного дослідження з метою виявлення потенційного дефекту для окремого елементу термограми визначається через функцію розподілу ймовірності температури, що співставляється з аналогічною функцією для однорідної ділянки тестового об'єкта. У рамках базової методики розподіл ймовірності для ділянки однорідної тестового об'єкта та ділянки тестового об'єкта зі структурними особливостями відрізняються показниками математичного сподівання і дисперсії. Через поділ області розподілу ймовірності температури пороговим значенням формуються чотири зоні: зона для якої дефект гарантовано відсутній, зона для якої дефект не фіксується у відповідності до вибору порогового значення, зона для якої дефект фіксується у відповідності до вибору порогового значення, зона для якої дефект гарантовано наявний. Базовий підхід, що на основі статистичних методів дозволяє визначити точність проведення термографічного аналізу для окремого елемента термограми через розрахунок співвідношення сигнал-шум на основі показників математичного сподівання і дисперсії розподілу ймовірності температури. У рамках розширеної схеми статистичного аналізу результатів термографічного дослідження визначається z-величина, базується на визначенні кількості сусідніх елементів термограми, що відповідають однорідній ділянці та ділянці з потенційними структурними особливостями.
Ключові слова: термограма, тепловий відгук, карта дефектів, статистичний аналіз, розподіл ймовірності, порогове значення, співвідношення сигнал-шум

O. Levinskyi, H. Oborskyi. **A comprehensive method of a defect map forming based on thermal response patterns.** The study considers contemporary approaches used in the analysis of infrared thermography results of a test object aimed at identifying structural features for defect map formation. Emphasis is placed on the advantages of employing statistical analysis methods in thermogram analysis, involving the quantitative assessment of signal-to-noise ratio and optimizing the thermographic analysis procedure through global extremum search of the objective function. According to the developed methodology, a set of four possible outcomes resulting from the thermographic analysis of a test object is examined, including true positive, false positive, true negative, and false negative results. The analysis of thermographic procedure results for the detection of a potential defect in an individual thermogram element is determined through the probability distribution function of temperature, which is compared with a similar function for a homogeneous section of the test object. In the basic methodology, probability distribution parameters for a homogeneous section of the test object and a section with structural features differ in terms of mean and variance. By dividing the temperature probability distribution area with a threshold value, four zones are formed: a zone where a defect is guaranteed to be absent, a zone where a defect is not detected according to the chosen threshold value, a zone where a defect is detected according to the chosen threshold value, and a zone where a defect is guaranteed to be present. The basic approach, based on statistical methods, allows determining the accuracy of thermographic analysis for an individual thermogram element by calculating the signal-to-noise ratio based on the fundamental indicators of mean and variance of the temperature probability distribution. Within the extended scheme of statistical analysis of thermographic investigation results, a z-value is determined, based on the number of neighboring thermogram elements corresponding to a homogeneous section and a section with potential structural features.
Keywords: thermogram, thermal response, defect map, statistical analysis, probability distribution, threshold value, signal-to-noise ratio

Introduction

Thermal methods of nondestructive testing constitute an important field within non-contact diagnostics which involve the analysis of thermal or infrared radiation emitted by test objects during the generation, conversion, transfer, and storage of thermal energy. Mathematical modeling of the influence of the test object's structure and existing defects on changes in thermal and thermomechanical

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properties allows for an assessment of material behavior under real operating conditions within the framework of thermographic investigations. This provides a basis for developing more reliable constructions and lays the methodological foundation for the automation and optimization of non-contact diagnostics procedures based on infrared thermography systems. The thermographic analysis procedure comprises two stages: defect detection using statistical methods and subsequent classification. The effectiveness of the classification stage significantly depends on mathematical models, as well as software algorithms and expert evaluation underlying the analysis. During the classification stage, parameters characterizing the shape, linear dimensions, and chemical composition are quantitatively determined by solving the inverse problem of the investigation. The minimum accuracy of the assessment is defined by the diagnostic procedure's task formulation in accordance with established norms and standards, as well as the necessity to address the task of further predicting risks associated with the operation of the test object. The foundation of thermographic analysis lies in temperature dependencies, enabling the determination of morphological features of the test object and the detection of structural violations such as layering of structural components, ruptures in the homogeneous environment of the test object, presence of flat cracks, presence of foreign inclusions, presence of contact areas with high thermal resistance, corrosion in the test object, and local variations in thermal properties within the test object's environment, including the appearance of areas with increased humidity, porosity, etc. This information is obtained by comparing detected anomalies with temperature patterns from a training dataset.

Analysis of recent publications and problem statement

The conducted analysis has indicated that the application of mathematical modeling methods in the field of infrared thermography enables the identification of principles governing the spread of thermal fluxes, depending on the structure of test objects and the surrounding environment [1, 2, 3]. This forms the basis for assessing the dynamics of thermal processes through temperature profiles. The analysis contributes to enhancing the accuracy of procedures based on Thermal Nondestructive Testing (TNDT) and expands the toolkit for non-contact diagnostics. It is noted that the corresponding task is nontrivial and involves determining the thermal properties of materials and the propagation of thermal waves depending on the environment, evaluating the influence of defect composition and shape on the thermal properties of test objects, modeling the process of infrared radiation propagation in a simulated environment, etc. [4, 5, 6]. Furthermore, it is emphasized that the mathematical model of the thermographic analysis system should include a subsystem of external thermal stimulation. This subsystem, utilized in the active operating mode of the diagnostic complex, incorporates heating and cooling modules that can be applied in a combined mode during the acquisition of infrared thermograms [7, 8]. It is also worth noting that in solving many non-contact diagnostic tasks based on infrared thermography, combined methods are employed, such as inductive heating of conductive structures followed by air cooling of the test object.

It is indicated that the spectrum of application fields for non-contact diagnostic instruments based on infrared thermography systems in industrial control and prediction is extremely broad. Thus, the mathematical modeling of the thermographic analysis system and the development of algorithms for processing the results of experimental research enable increased efficiency in non-contact diagnostics in relevant areas of industrial monitoring:

1. Thermographic analysis of industrial premises and complexes [9, 10], including the detection of concealed defects, assessment of thermal resistance of walls, roof diagnostics to identify elevated moisture levels, and inspection of chimneys and ventilation ducts.

2. Thermographic analysis of electrical systems and equipment [11, 12] in an industrial environment, involving diagnostic studies of transformers, switching systems, protective devices and limiters, electric generators and motors, as well as additional components of electrical equipment.

3. Thermographic analysis of thermogenerator systems [13, 14] in an industrial environment, comprising diagnostic investigations of thermal generators, steam complexes, cooling systems, thermal networks, heating complexes, and vacuum equipment of power generators.

4. Thermographic analysis of metal components and joints [15, 16] in industrial objects, incorporating temperature control during welding, prediction of the service life of cutting tools based on thermal conductivity indicators, detection of corrosion in metal components, and diagnostics of rolled metals and composite materials.

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5. Thermographic analysis of mechanisms and technical equipment [17, 18], encompassing components of transportation systems, aviation structures, etc.

It is noteworthy that the thermographic analysis of industrial premises and complexes serves as the initial stage in establishing a monitoring system at an enterprise for conducting planned diagnostic procedures and organizing a prediction subsystem based on machine analysis. For example, the detection of concealed defects allows identifying uncontrolled heating, thermal leaks, or damage to insulation, with the aim of assessing the danger level of subsystem overheating or fire and taking necessary measures for their elimination.

Purpose and objectives of the study

Thus, the purpose of the research is to develop a comprehensive methodology for data processing in automated infrared thermography systems, which includes the detection and classification of structural features within the test object environment. This methodology should encompass the following components:

– determining statistical parameters during the thermographic analysis of the test object;

– generating a defect map of the test object based on experimental data;

– identifying patterns of thermal response from the object during thermographic investigations in an active mode;

– detecting and compensating for noise that arises during thermographic investigations.

Sequential execution of these stages allows for increased efficiency in defect detection within the test object, accuracy in determining relevant parameters, and the ability to forecast the further operation of the respective equipment. Additionally, it enables the formulation of methodological recommendations for optimizing the thermographic analysis procedure.

Statistical Analysis of Thermographic Analysis Results

The foundation of the methodology for determining structural features of the test object and forming a defect map based on thermal response patterns during the thermographic analysis procedure should be based on defining the complete set of possible outcomes:

1. True Positive (TP): The accurate detection of a defect. The probability that an existing defect in the structure of the test object will be identified during the diagnostic procedure is expressed by the value P_{TP}.

2. True Negative (TN): The accurate identification of the absence of a defect. The probability that the diagnostic procedure will correctly determine the absence of a defect in a homogeneous structure of the test object is expressed by the value P_{TN}.

3. False Positive (FP): Incorrectly detecting a defect. The probability that the diagnostic procedure will mistakenly indicate the presence of a defect in a homogeneous structure of the test object is expressed by the value P_{FP}.

4. False Negative (FN): Incorrectly not detecting a defect. The probability that an existing defect in the structure of the test object will not be identified during the diagnostic procedure is expressed by the value P_{FN}.

It should be noted that the sums $P_{TP} + P_{FN} = 100\%$ and $P_{TN} + P_{FP} = 100\%$ are unambiguously determined, in accordance with statistical theory, as illustrated in Fig. 1.

Let's consider the region of the test object subject to thermographic analysis as a matrix of constituent elements, TO(x, y), with dimensions $X_{TO} \times Y_{TO}$. We will examine the results of thermographic analysis at the defect detection level for an individual element of the thermogram with coordinates $\{x, y\}$, for which the temperature parameter at time t_0 is determined, corresponding to the peak of thermal stimulation in pulsed mode. The homogeneous area of the test object and the presence of non-uniformity, indicative of the presence of a defect, are characterized by the probability distribution function for the temperature indicator, denoted as $f_P(T)$.

In Figure 2, an example of the probability distribution for the temperature parameter is illustrated for an individual element $\{x_0, y_0\}$ of the test object surface matrix, corresponding to the distribution for a homogeneous area for the purpose of defect detection. The probability distribution for the temperature parameter of the homogeneous area of the test object is characterized by defined indicators of the mathematical expectation μ_{TO} and dispersion σ_{TO}. This allows, under the conditions of conducting a series of experiments, to identify areas with anomalous temperature behavior through discrepancies $\mu_{TO} \neq \mu_{NH}$ and $\sigma_{TO} \neq \sigma_{NH}$, where μ_{NH} and σ_{NH} are the indicators of mathematical expectation and dispersion for non-homogenous area, even if, within the scope of a particular study, the temperature value falls within acceptable limits. As can be observed, the probability distribution functions overlap, creating a region of uncertainty (the corresponding area is marked in gray on Fig. 2). The division of the uncertainty region by the threshold temperature value T_{TH} can be performed at the intersection point of the functions $f_P^{OT}(T)$ and $f_P^{NH}(T)$. This, in turn, divides the temperature axis into four zones:

1. Zone where a defect is guaranteed to be absent (TN zone).
2. Zone where a defect is guaranteed to be present (TP zone).
3. Zone where a defect is not detected based on the choice of T_{TH} (TN/FN zone).
4. Zone where a defect is detected based on the choice of T_{TH} (TP/FP zone).

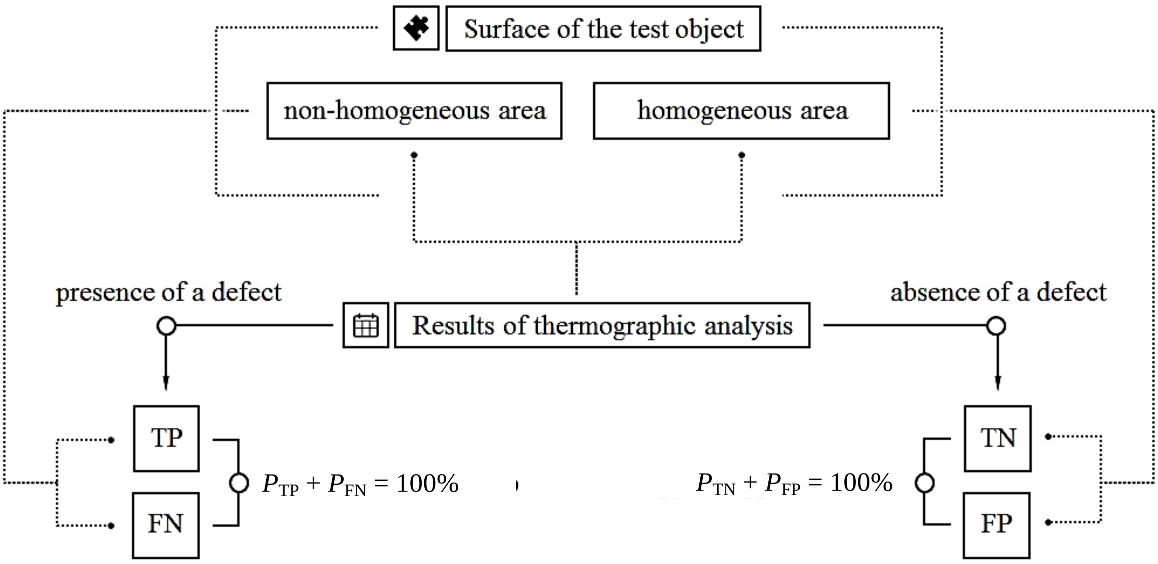

Fig. 1. Statistical distribution of the test object areas thermographic analysis results

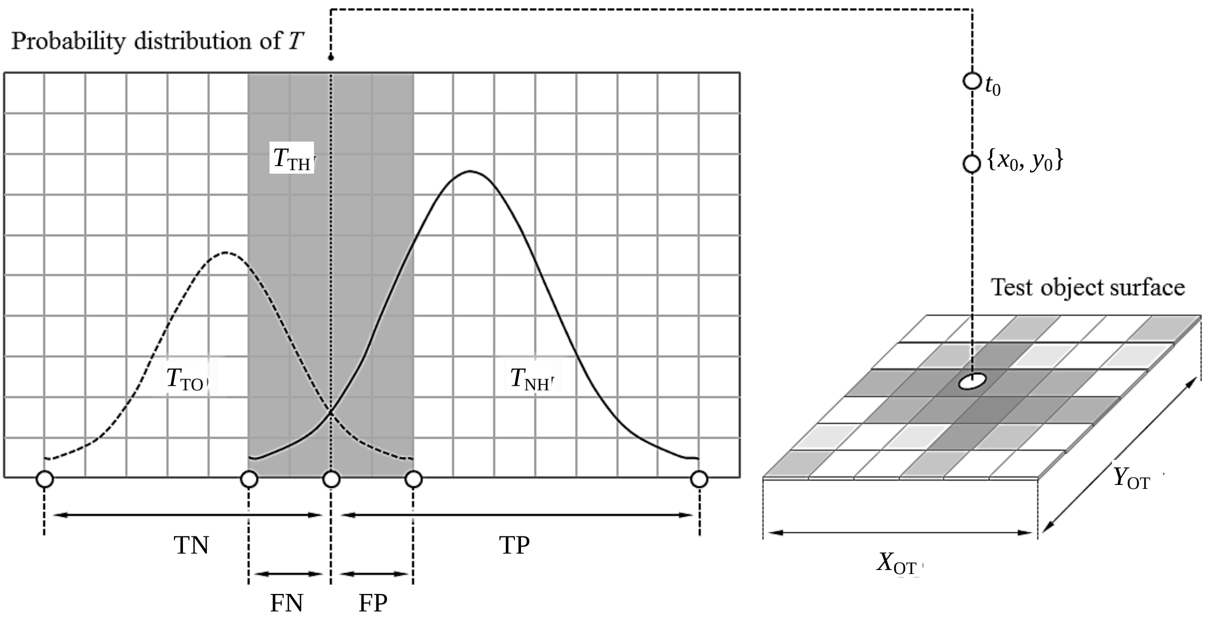

Fig. 2. Methodology for assessing the presence of a defect for an individual element of the thermogram through the analysis of the probability distribution for temperature

The basic approach, based on statistical methods, allowing for the precise determination of non-uniformity for an individual element of the thermogram, involves calculating the signal-to-noise ratio (SNR). For a normal distribution of the probability density of temperature in a homogeneous area of the test object and an area with structural features, the value of target function SNR(x, y) is determined based on the indicators of mathematical expectation and dispersion:

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$$\left[\begin{array}{l} \mathrm{SNR}(x,y)=\dfrac{\left|\mu_{\mathrm{NH}}(x,y)-\mu_{\mathrm{TO}}(x,y)\right|}{\left|\sigma_{\mathrm{NH}}(x,y)-\sigma_{\mathrm{TO}}(x,y)\right|}\times 100\% \\ \quad \text{for} \quad \left|\mu_{\mathrm{NH}}(x,y)-\mu_{\mathrm{TO}}(x,y)\right|<\sigma_{\mathrm{NH}}(x,y); \\ \qquad\qquad \mathrm{SNR}(x,y)=100\% \\ \quad \text{for} \quad \left|\mu_{\mathrm{NH}}(x,y)-\mu_{\mathrm{TO}}(x,y)\right|\ge\sigma_{\mathrm{TO}}(x,y). \end{array}\right. \tag{1}$$

This indicates that under conditions where the probability distribution for a homogeneous area of the test object does not intersect with the corresponding distribution for an area with structural features, which may indicate the presence of defects, the signal-to-noise ratio is considered equal to 100%. It should be noted that within this approach, during machine analysis, the complete set of relevant indicators is not included, indicating its low efficiency. In this study, we propose the foundation of an extended statistical analysis scheme of thermographic investigation results, based on determining the z-statistic. Beyond determining the indicators of mathematical expectation and dispersion for the homogeneous environment of the test object and areas with structural features, the quantity of neighboring elements $\{x\,\sigma_{\mathrm{TO}}(x,y)\,\{x\pm 1;\ y\pm 1\}$ without defects and with defects within a limited area around the analyzed element must be evaluated, denoted as N_{TO} and N_{NH}, respectively:

$$z=\frac{\left|\mu_{\mathrm{Def}}-\mu_{\mathrm{TO}}\right|}{\sqrt{\dfrac{(\sigma_{\mathrm{Def}})^2}{N_{\mathrm{Def}}}-\dfrac{(\sigma_{\mathrm{TO}})^2}{N_{\mathrm{TO}}}}}\,. \tag{2}$$

The z-value is then compared with the threshold value z_{TN}, determined based on the probability of FP.

Additionally, it should be noted that incorporating the analysis of time dependencies in thermograms, determined during thermal stimulation of the test object in pulsed mode, as well as the amplitude-frequency characteristics (AFC) and phase-frequency characteristics (PFC) obtained through Fourier transformation, as discussed in the previous section, significantly enhances the accuracy of conducting defect inspection of the test object and substantially expands the researcher’s toolkit.

Formation of a defect map based on thermal response patterns

In accordance with the aforementioned procedures for determining statistical parameters of thermographic data acquired during a diagnostic procedure of a test object, a binary defect map can be constructed. This map is represented as a two-dimensional matrix Def(x, y) with dimensions $X_{\mathrm{TO}}\times Y_{\mathrm{TO}}$, where Def($x$, y) = 0 corresponds to an element in the test object region without any defects, and Def(x, y) = 1 corresponds to an element in the test object region potentially containing a defect. For the test object region potentially containing a defect, false alarm probability and correct detection probability are determined based on a threshold value in the thermographic analysis procedure.

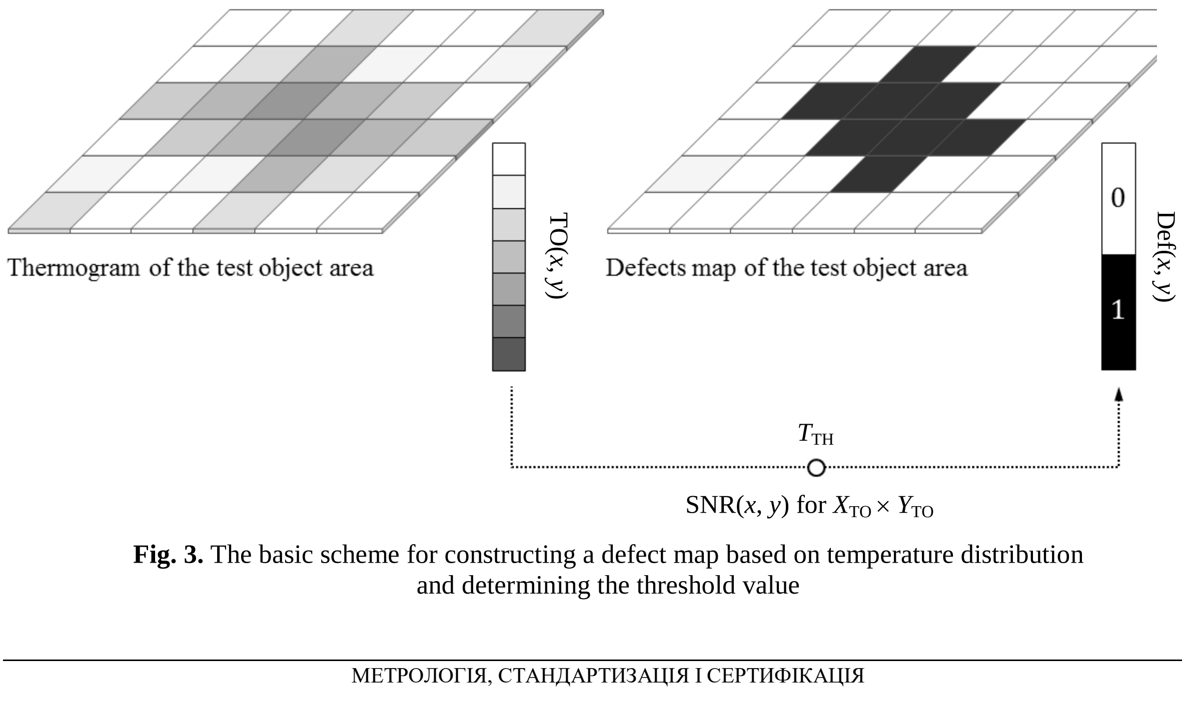

Fig. 3. The basic scheme for constructing a defect map based on temperature distribution and determining the threshold value

The most straightforward method for determining the value of an individual element on the defect map is the application of a threshold temperature value, calculated in accordance with P_{FP} and P_{TN}, as well as the probability distribution. Other indicators, such as the temporal dependence of temperature, frequency response and phase response, serving as thermal response patterns, may also be utilized as threshold values. Additionally, their combination allows for the subsequent correlation of values in areas with a high probability of false defect detection. This significantly simplifies the transition from a binary defect map to a multi-level map of structural features of the test object, where levels may correspond to the depth of inhomogeneities, concentration of foreign inclusions, differentiation between surface contamination and corrosion of the test object, etc. The detection and classification of the multi-level defect map represent a standard pattern recognition task in a multidimensional space. Mathematically, this corresponds to the problem of estimating parameters of a hyperplane to identify defective areas and classify defects. This is accomplished using software algorithms and deep learning neural network architectures, where corresponding training datasets are formed. In turn, the high efficiency of incorporating additional parameters into thermogram analysis is associated with their weak interdependence, providing the opportunity to correlate the assessment obtained at the level of machine analysis, based on data from several independent sources.

Conclusions

The conducted research thus encompasses the identification of modern approaches employed in data processing within infrared thermography, particularly defect detection using statistical methods. Within the framework of the research on data processing methods, the following approaches have been proposed:

1. A methodology for assessing the presence of defects in the test object environment based on a set of elements in the thermogram matrix through the analysis of the probability distribution.
2. A methodology for determining thermal response patterns and forming a defect map.

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