

Defect Characterization of Plain Carbon Steel through Infrared Thermography Non-Destructive Testing and Image Processing Using Matlab

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Abstract: Composite materials and Carbon steel structures are widely used in the field of aerospace field. Some of these materials may be prone to premature degradation caused by poor design, manufacturing defects, or construction mishandling. This may lead to extension of internal anomalies and damage to whole body of the component, unless the state of the materials evaluated properly at the time of manufacturing. For a long time many techniques have been available to test objects which are based on contact type inspection which makes a minute destruction to the sensitive areas of anomalies at the time of inspection which are present in materials. Lock-in Thermography which is a non-contact mode active thermography technique for NDT is based on propagation and reflection of thermal waves which are launched from the surface into the inspected component by absorption of modulated radiation. Phase Angle images and Amplitude images obtained by superposition of the initial thermal wave and its internal reflection display hidden thermal structures down to a certain depth below surface. Defects are found by comparing the observed features with expected features provided by theory or by an intact reference sample. This technique has been widely applied to detect the defection of composite materials and structures in active heat source into sample, and the thermal wave image sequences are collected and special image sequence file formation The experimental results show that the lock-in thermography (IRNDT) software system can be used to detect the subsurface defects even in micron level. The shape and size of the defect can be characterized by image processing technique with the help of MATLAB.

Keywords: Material defects, IRNDT, Lock-In Thermography, and Image Processing.

I. Introduction:

^[1]Thermography means the mapping of Isotherms, or contours of equal temperature over the surface of a component. ^[7]Infrared Thermography is a non-contact mode of Non-Destructive Testing of materials in which a heat-sensitive device is used to measure the intensity of Infrared (IR) energy emitted from the surface. Heat sensing materials or devices can be used to detect irregularities in temperature contours and such irregularities can be related to defects. It mainly focuses on Thermal Pulse Video Thermography in which no physical contact is necessary with the inspected material and very rapid rates of inspection are possible. A high-intensity heating source is used to send pulses of Infrared (IR) energy into the material.

Pulses of heat energy from a source are directed at the component under. It is usual, but not essential, to direct the incident energy onto one surface of a component and observe the defects at the opposite surface after conduction through the material. ^[3]Flaws and irregularities in structure will affect the amount of conduction in their vicinity. If it is impossible to have access to both surfaces, the technique can still be used. The heat energy incident on the surface will be conducted away through the material at differing rates, depending on whether or not flaws are present. Flaws and irregularities in structure will affect the amount of conduction in their vicinity. The lower the lock-in frequency is, the larger is the information depth of lock-in thermography. The advantage of lock-in thermography is that due to its averaging nature its sensitivity may improve considerably compared to the normal sensitivity of the camera used. Therefore, lock-in thermography is very advantageous tool in NDT and Failure analysis.

^[5]The surface is scanned by an IR thermal images with a TV video output. This system, can either be used for sensing heat transmitted through the component or for single-sided inspection when only one surface is accessible. Very good sensitivities are possible. ^[2]Digitized Image Processing to provide image enhancement is also possible.

II. Experimental Set Up:

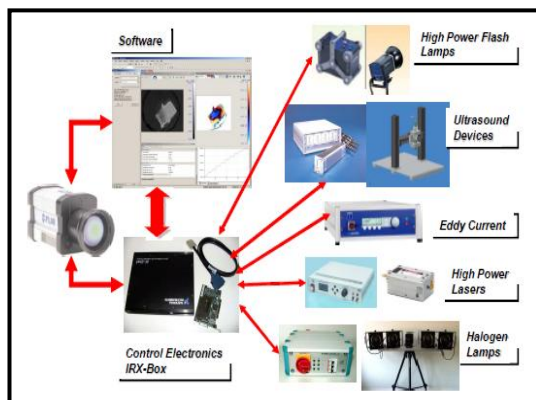


Fig 1: Various primary excitation sources for equipment setup

IR-NDT is an all-purpose modular real-time infrared imaging system for all kind of non- destructive inspections with active thermography. It supports all known measurement techniques (Lock-in, Pulse, Transient, Vibro-Thermography, and TSA) with all kind of excitation sources (optical, ultrasound, eddy current, microwave, and stress-strain test rig. The integration into test stands or into a production line is very easy: the system uses the latest automation interfaces for direct control, communication and data exchange with other components (e.g. computers, PLCs). It provides fully automated measurements with automatic data archiving. All connections are established with a multifunctional interface box. The box can easily be upgraded with standard modules (e.g. for the connection of additional sensors). The system can be used together with a wide variety of infrared cameras from non-cooled devices with micro bolometer detector up to highly sensitive stirling-cooled high-speed cameras. If an infrared camera with a radiometric calibration is connected to the system, it can also be used for temperature measuring tasks with passive thermography.

III. Working Principle:

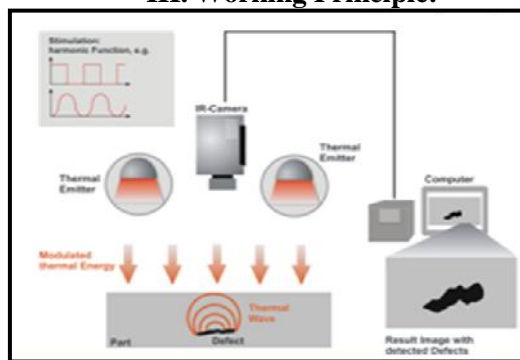


Fig 2: Schematic Diagram of Lock-In Thermography

^{[1][5][6]}The principle of the Lock-In Thermography is based on creating a thermal wave on the surface of the object being examined by periodic energy input. This wave moves into the object in and with increasing distance of the surface is absorbed and negatively phase shifted. If the wave reaches areas of the object, within which the thermophysical properties change (e.g. at delamination or inclusions), it is partly reflected. The reflected part interferes with the wave created at the surface, whereby an interference pattern in the local surface temperature and thus in the surface radiation is caused, which oscillates with the frequency of the thermal wave. By evaluating the amplitude and the phase of the local surface temperatures one gets information about the internal structure of test object. Since with the procedure interference patterns are analyzed, it plays a role for the applicability that these can occur clearly only if the material thickness corresponds approximately to the wavelength of the thermal wave and if there are actually differences in the thermophysical properties in the structure of the item. The thermal wave at the surface of test object is not only influenced by reflections at the inner structure. Some further object parameters, e.g. porosity, have effects on the temporal and local behavior of the temperature oscillation. Thereby it is possible to compare objects with each other in relation to a variation of these properties. A substantial advantage of the Lock-In Thermography is in the fact that by the use of a periodic

stimulation detailed examinations can be executed with a relatively small energy input into the object. This permits the examination of thermally sensitive components and the use of relatively simple heat sources. For measuring the local oscillations of the surface temperature an infrared camera with high frame rate and high thermal and geometrical resolution is used. The detector of this camera measures the radiating power outgoing from the object surface. After a previous calibration it can also calculate the local temperature according to Planck's radiation law.

IV. Lock-In Evaluation:

^{[2][3]}By recording an infrared image sequence, information is available for the evaluation of the amplitude and phase of the temperature oscillation for each individual pixel in the image. Each pixel can be regarded here as a discrete measuring point on the surface of test object, so that one receives a high geometrical resolution with the infrared cameras supported by IRNDT. For the analysis the software provides various different methods of analysis.

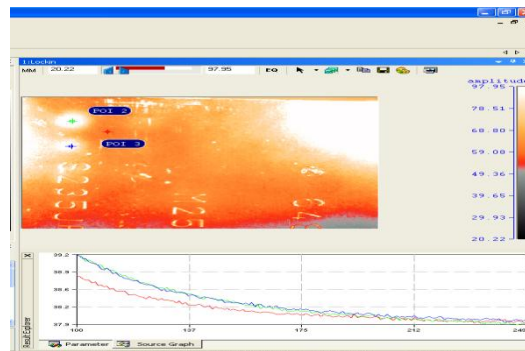


Fig 3: Lock-In image where defects are revealed

^{[4][6]}The IRNDT software covers the complete functionality to perform non-destructive and non-contact inspections with active thermography on parts from different materials. IRNDT controls the hardware and stores the infrared images from the camera in real time. With its high performance imaging algorithms the software evaluates result images showing defects inside inspected parts. Export of measurement data into different formats: such as MATLAB, Excel, and BMP. Extension modules are available which support the data evaluation for the different measurement techniques.



Fig 4: Lock-In Thermography image using IRNDT

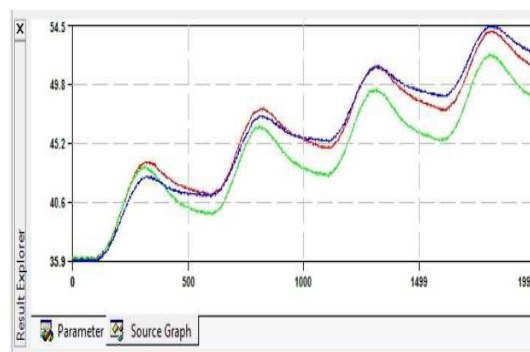


Fig 5: Source Graph generated for various thermographic images (Thermograms)

With the graph, a direct impression of the behavior of the signal at the surface of the test object (amplitude, signal-to-noise ratio, drift of the signal). This information is very helpful for choosing the evaluation parameters (e.g. the start image). Furthermore to get an indication, if the measurement with the chosen method, camera, excitation source and parameters is applicable for the measuring task. If for example it could be seen only a very low amplitude and large noise within the graph, it cannot expect a good result image. By default there is one plot displayed in the window, which represents the pixel marked with a cross-hair in the image. The cross-hair can be dragged with the mouse pointer to any position within the image. From the toolbar of the evaluation view it can add cross-hairs to mark other pixels and to get additional signal-time-plots. Thus it can compare the signal behavior at different positions within the image.

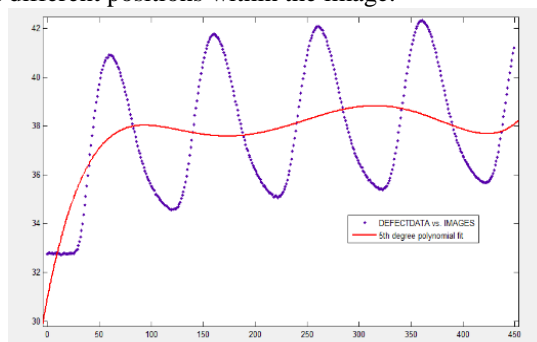


Fig 6: Curve fitting Graph plotted through MATLAB

In the graph the measured signal (red) as well as the approximated analytical function (blue) is displayed. For the evaluation it's essential that there is a good match between the analytical function and the measured signal. If there are strong deviations, the evaluation method is not applicable. Because of the analytical approach the evaluation method, the amplitude and the phase information can be calculated.

V. Calculations:

In order to derive the equation for the depth range of the thermal wave in solid materials, one must proceed from the common differential equation for thermal conduction:

$$\frac{\partial^2 T}{\partial z^2} = 1/\alpha \frac{\delta T}{\delta t};(1)$$

In the following presented one-dimensional case the solution has the shape of an oscillation with a damping factor and a proportion, which describes the phase shift.

$$T(z, t) = T_0 e^{-\sqrt{\frac{\omega \rho c}{2\lambda}} z} \cos(\omega t + \sqrt{\frac{\omega \rho c}{2\lambda}} z);(2)$$

- λ = Thermal Conductivity
- ω = Angular Frequency, $2\pi \cdot f_e$ (Excitation Frequency)
- ρ = Density
- c = Specific Heat Capacity
- z = Coordinate

As one can see, the decrease of the amplitude of the thermal wave with increasing material depth depends on the thermophysical properties and the stimulation frequency. Within a depth of

$$\mu = \sqrt{\frac{2\lambda}{\omega \rho c}} = \sqrt{\frac{2a}{\omega}} \text{ mm} \quad : \quad (3)$$

The amplitude drops to 37% (1/e) of the surface value. The characteristic length m is called thermal penetration depth. It is a function of the thermal diffusivity of the examined material and of the excitation frequency.

VI. Experimental Results of C30 Carbon Steel:

Where Thermal Conductivity of Carbon Steel, $\lambda = 68 \text{ W/}^\circ\text{K}$

Excited Frequency, $f_e = 0.25 \text{ Hz}$

Density, $\rho = 7840 \text{ kg/m}^3$

Specific Heat Capacity, $C_p = 0.49 \text{ KJ/kg.K}$

Depth of Penetration of Thermal Wave, $\mu = \frac{2\lambda}{\omega \rho c_p} = 0.022 \text{ mm}$

Therefore, the actual known thickness of C30 Carbon Steel Sample is 6mm, where ^{[1][3]} Lock-In thermography technique reveals the defects up to 0.022 mm depth.

VII. Image Processing In MATLAB:

^{[2][7]}The basic data structure in MATLAB is the *array*, an ordered set of real or complex elements. This object is naturally suited to the representation of *images*, real-valued ordered sets of color or intensity data. MATLAB stores most images as two-dimensional arrays (i.e., matrices), in which each element of the matrix corresponds to a single *pixel* in the displayed image. (Pixel is derived from *picture element* and usually denotes a single dot on a computer display.)

For example, an image composed of 200 rows and 300 columns of different colored dots would be stored in MATLAB as a 200-by-300 matrix. Some images, such as true color images, require a three-dimensional array, where the first plane in the third dimension represents the red pixel intensities, the second plane represents the green pixel intensities, and the third plane represents the blue pixel intensities. This convention makes working with images in MATLAB similar to working with any other type of matrix data, and makes the full power of MATLAB available for image processing applications.

- To Read Image in the MATLAB, then type `I = imread('steel.jpg');`
`Imshow (I)` in command window

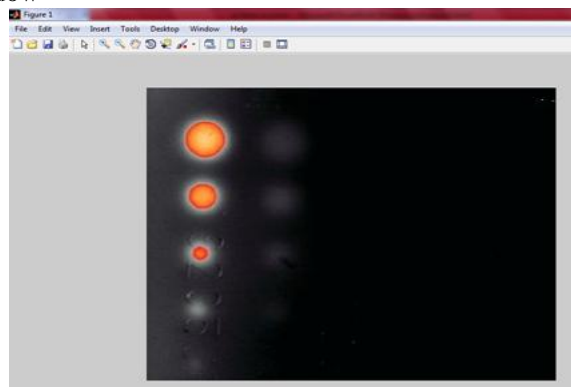


Fig 7: Shape of the defect is determined using image processing technique

- To view the defects in color map
`[label, num]=bwlabel(d,4);`
`imagesc(label);`

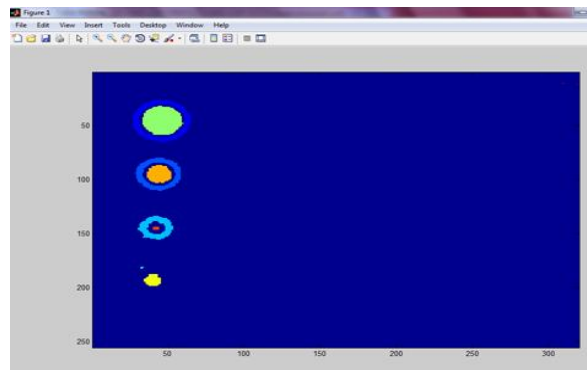


Fig 8: Color mapping of the defect is applied using image processing technique

- To know the region where maximum Area and Centroid are :

```
stats=regionprops(label, 'basic');  
max_area=max([stats.Area]);  
biggrain=find ([stats.Area] ==max_area);  
stats(biggrain).  
Centroidans = 46.5153 45.3321
```

- To view the given sample with defects in 3D Surface view:

```
surf(steel,'DisplayName','steel');figure(gcf)
```

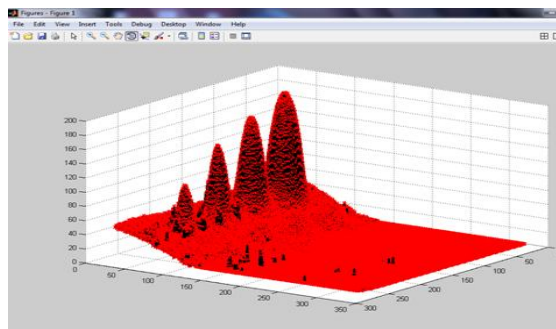


Fig 9: Size of the defect is determined

VIII. Conclusions:

^[3]The results presented in this paper show the IR Lock-In thermography non-destructive test system based on image sequence processing is an effective tool of non-destructive testing for detection sub-surface defects for many materials. This method can be used both in phase of production of materials as well as at inspection during the service time of a construction formed from this material. This program have an important advantage of this method is that can sweep many modulated frequencies from the image sequence, and the optional modulate frequency can be obtained quickly, and IR Lock-In thermography method is non-contact for materials under various applications.

IX. References:

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