Structural integrity assessment of materials by thermography

N.P. Avdelidis[1*], D.P. Almond[2], C. Ibarra-Castanedo[3], A. Bendada[3], S. Kenny[4], X. Maldague[3]

[1] Metallurgical Industrial Research & Technology Development Centre – EBETAM, RTD Department, A' Industrial Area of Volos, Volos 38500, Greece.
[2] Materials Research Centre, University of Bath, Bath BA2 7AY, United Kingdom.
[3] Computer Vision & Systems Laboratory, Department of Electrical & Computer Engineering, Laval University, Quebec City, G1K 7P4, Canada.
[4] NDT Group, TWI Technology Centre in Wales, ECM[2], Port Talbot, SA13 2EZ, United Kingdom.

ABSTRACT

Thermographic approaches, passive and active, are widely used due to the outstanding advantages that offer in a number of applications and particularly for the assessment of materials. Nonetheless, there are limitations; depending upon the approach used, as well as on the materials thermal, optical and physical properties, proper assessment (detection and/or quantification) is feasible. In this work, different applications, employing thermographic testing, concerning the assessment of various materials are presented. The following applications are included:

- Through skin sensing development & trials on aircraft materials (Al-2024T3 & CFRP).
- Assessment of defects under composite patching.
- Quality assurance and structural evaluation of GRP pipes by using PT.

The results of this study show that thermography can be used successfully for the structural integrity assessment of different materials and/or components.

1. Introduction

Infrared thermography for non-destructive testing and evaluation (NDT & E) aims at the detection of subsurface features (i.e. subsurface defects, anomalies, etc.), owing to temperature differences (ΔT) observed on the investigated surface during monitoring by an infrared camera. At temperatures above absolute zero all bodies emit electromagnetic radiation. Infrared thermography or thermal imaging is a measurement technique based on the detection of radiation in the infrared spectrum (usually in the 2-5.6 μm and 8-14 μm regions). These two spectral bands are commonly used because of their low atmosphere absorption.

The principal problem where infrared measurements are concerned is the emissivity [1], emittance of the material(s). Provided that an infrared camera detects and records the radiation emitted by a material under investigation and renders this energy to a temperature – thermal image, the characteristic that describes the relation between the emitted radiation and the material's temperature, is termed as emissivity. Emissivity is actually a surface property that states the ability of the investigated material to emit energy. Values for emissivity (ε) can be between 0 (perfect reflector – mirror) and 1 (perfect emmiter – blackbody). As a result, emissivity plays an essential role in infrared thermographic surveys and is dependent on temperature, wavelength and surface condition. A surface with a low emissivity value (i.e. aluminium, steel, etc.) acts as a mirror (high reflectance). However, such problem is usually overcome using high emittance flat paints (i.e. black colour water based paints) for painting the investigated surface(s).

* Correspondence: Email: avdel@mail.ntua.gr

2. Approaches

Infrared thermography is deployed by two approaches; passive and active. With the passive approach thermography is used to investigate materials that are at different temperature than ambient (often higher), whilst in the case of the active approach an external stimulus source (i.e. optical flash lamps, heat lamps, hot or cold air guns, etc.) is used in order to induce relevant thermal contrasts. The most regular applications of the passive approach in NDT & E are for buildings and infrastructures, maintenance, components and processes, and medicine. In most situations, passive thermography is used for qualitative assessment (although this is not always the case), given that the objective is to detect irregularities of the kind function or malfunction.
The active approach has also several applications in NDT & E. The temperature differences during the transient phase appear on the material surface and so detection of subsurface defects is possible (areas of different temperatures when compared to the sound part(s) due to the different thermal diffusivity). Since the heating or cooling features of the stimulus source are identifiable by considering the time factor quantitative assessment is also feasible. The most common modes of active thermography are pulsed thermography, long pulsed heating or step heating transient thermography, optical lock-in thermography, and ultrasound lock-in thermography.

3. Advantages – Limitations

The main advantage of infrared thermography over the destructive testing techniques is that large areas can be scanned fast and with no need to be destroyed during testing. This results in major savings in time, people, work and machinery. In addition, there are advantages of infrared thermography over the other non-destructive techniques. The infrared thermographic device is risk-free, as it does not emit any radiation; it only records the infrared radiation emitted from the material that is under assessment. Moreover, infrared thermography is an area investigating technique, whereas most of the other non-destructive methods are either point or line testing methods. Furthermore, infrared thermographic testing may be performed during both day – and night – time hours.
Thermography, due to the fact that it uses infrared technology it is not possible to penetrate in extended depths (only a few mm's). That of course is one of the main limitations of the technique. Finally, environmental conditions also play an important role on outdoor infrared thermographic surveys utilising the passive approach (i.e. cloud cover, solar radiation, wind speed).

4. Applications

Although the use of infrared thermography is found to be extensive mainly in terms of research purposes in NDT & E, a number of applications are presented in this section.

<u>Through skin sensing development & trials on aircraft materials (Al-2024T3 & CFRP)</u>

The objective was to study the ability of pulsed thermography for locating anchoring points beneath the outer skin of aircraft structures, to facilitate automated drilling and fixing [2]. Typical test structures, comprising of carbon fibre reinforced plastic (CFRP) aircraft skin positioned over a thick CFRP strut fixture, were investigated experimentally and analysed using finite difference thermal modelling software, taking into consideration the size and depth of the features, as well as their thermal properties. The ability of pulsed thermography to detect a subsurface fixing and to offer information about its location was investigated.
The representative test structures (comprising of either 2mm or 4mm CFRP aircraft skin positioned over a thick CFRP strut) were analysed using the ThermoCalc-3D software. The dimensions of both panels were 500 mm x 500 mm. The skin thickness of the CFRP was either 2 mm or 4 mm and the width of the strut was 100 mm. The size and depth of the

features, as well as the thermal properties of the investigated materials were taken into account. Furthermore, the effect of thermal contact resistance (air gap between skin and strut) was also considered. For this reason, the models were run using different values of air gap such as 1, 10, 50 and 100 μm, as well as with having the perfect contact between the two surfaces (zero air gap). Different heating time parameters were used for the models.

Material	Thermal Conductivity ($Wm^{-1}K^{-1}$)	Heat Capacity ($JKg^{-1}K^{-1}$)	Density (Kgm^{-3})	Heat Time (s)	End Time (s)	Time Step (s)
CFRP (⊥ fibre)	0.8	1200	1600	0.003	5	0.05
CFRP (|| fibre)	7	1200	1600			
Air	0.026	1007	1.16	-----	-----	-----

Table 1: Parameters used during modelling

It was seen that the peak contrast of the 4mm CFRP skin over the CFRP strut is 2 times smaller than that of the 2mm CFRP skin over the CFRP strut, whilst its time scale (thermal transient phase) was four times longer. The modelling results gave also a good indication of how each tested structure responded to thermal heating. It showed the differences between two low thermal conductive materials (i.e. CFRP) with different skin thickness after being heated with a thermal excitation source uniformly. Furthermore, it was found that as the air gap between the two surfaces (poor contact) was increased, the thermal contact resistance was increased and therefore poorer results were obtained. This can be seen from figure 1, where the peak contrast ΔT values against the air gaps modelled are plotted for both tested structures.

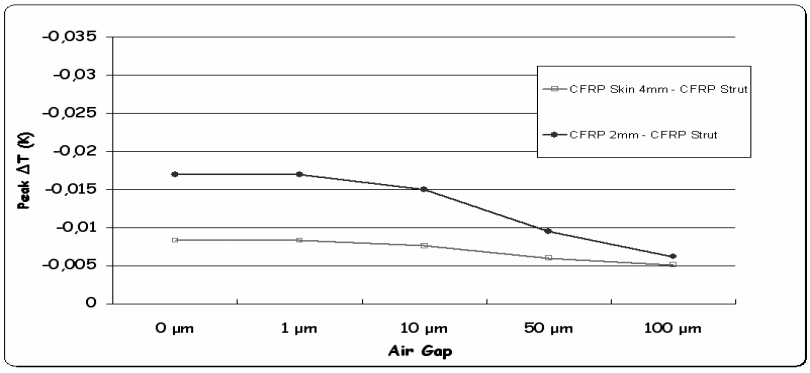


Figure 1: Thermal modelling results of peak strut contrast as a function of air gap for modelled structures

An integrated pulsed thermography system (Thermoscope) using a medium wave infrared camera (Merlin) was utilised for the experimental work. The two panels that were modelled were also examined during this experimental work. In the case of the 2mm CFRP skin, its dimensions were 240 x 243 mm (width x length), whilst the dimensions of the 4mm CFRP skin was 300 x 275 mm (width x length). The width of the CFRP strut in both situations was 62.4 mm and its thickness 5 mm. In the case of the 2mm CFRP skin positioned over the CFRP strut, G-clamps were used in order for the skin to be attached to the strut, whilst in the case of the 4mm CFRP skin over the CFRP strut, a specialised test rig was used, applying various loadings – pressures. The lay-up of the fibres on the CFRP skin was: $[(\pm 45°, 0_2, 90_2°)_2]_2$.

In the case of the CFRP skin of 2mm over the CFRP strut, due to the relatively low thermal conductivity of the CFRP the thermal images during the cooling down process were acquired with a frame rate of 7.49 frames per second, whilst in the case of the 4mm CFRP skin over the CFRP strut, due to the relatively sizeable skin thickness the thermal images during the cooling down process were acquired with a frame rate of 3.75 frames per second. A line was

marked on the skin surface to show the centre line of the strut. The contrast of the thermal images of the subsurface fixtures in relation to time was measured (plots of contrast –vs.- time). Information concerning the centre line of the struts was obtained from the thermal images.
As far as the thinner CFRP panel is concerned (i.e. skin thickness of 2mm), it was found that the subsurface strut could be imaged satisfactorily, using the conventional thermal image. The images were very similar to the modelling simulations. The centre of the strut was taken as being mid-way between the two half minima locations of the contrast (from typical line profiles). Five line profiles along the X-axis at Y pixel values of 20, 74, 128, 182 and 236 were taken and the pixel values estimated to define the centre of the strut were attained. It was seen that at relatively early times (i.e. up to 5.344 seconds) the best results were accomplished, since there was no variability. The greatest variability was seen at the longest transient time (i.e. 30.06 seconds). However, the overall result showed great consistency, as the largest variability was 1 pixel (i.e. ~ 0.465 mm).

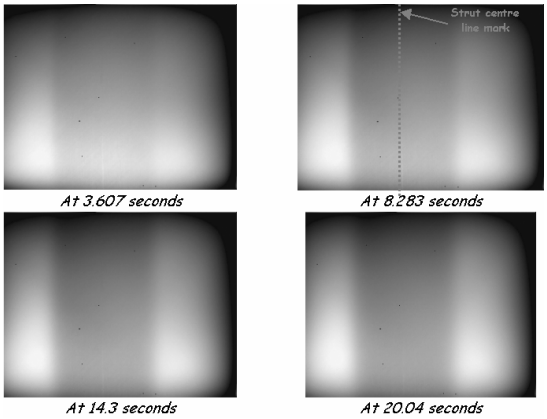


Figure 2: A selection of thermal images showing the strut beneath the 2mm CFRP skin

In the case of the 4mm CFRP skin over the CFRP strut, it was found that the 1st time derivative presentation of thermographic data was necessary to show the location of the strut. The pixel numbers of the two half minimum signal points were determined from X-axis line profiles and the strut centre was then estimated to be mid-way between these two points. 5 X-axis line profiles at the same Y-axis values were acquired at various times in a loading of 0.490kN, in order to estimate the centre line of the strut during the transient phase of the thermographic data; at relatively early times (i.e. up to 6.4 seconds) the best results were accomplished, since there was very little variability.

Assessment of defects under composite patching.

A composite repair patch [3] was investigated both experimentally and by modelling, with the intention of assessing an artificially introduced delamination (Teflon). The patch was a 6-ply boron epoxy composite material that was applied on an Al 2024-T3 surface. The dimensions of the Teflon were 25 mm x 25 mm and it was positioned between the 3rd and 4th ply of the composite patch (120 mm long x 70 mm wide). The thickness of each ply was 125 μm.
Experimentally the panel was investigated using a portable state-of-the-art thermographic system (Thermoscope) with an integrated flash heating system (duration of flash heating time 3.1 ms) employing a medium-wave infrared camera (Merlin 3-5 μm by Indigo). The infrared camera uses a cooled indium antimonide detector with a frame rate of 60 Hz, a focal plane array pixel format of 320 (H) x 256 (V) and an optical lens of 13 mm focal length.
For the purposes of thermal modelling, the ThermoCalc-3D software was employed. It is based on solving a heat conduction problem by means of an implicit finite-element numerical scheme. The software was used in order to calculate the three-dimensional (3D) temperature distributions of the various layers of the panel and provide information about the delamination in space and in time. The specimen was heated uniformly, whilst the thermo-

physical properties and heating time parameters shown in table 2 were used for the modelling.

Material	Thermal Conductivity ($Wm^{-1}K^{-1}$)		Heat Capacity ($JKg^{-1}K^{-1}$)	Density (Kgm^{-3})	Heat Time (s)	Time Step (s)	End Time (s)
	X axis	Y & Z axes					
Boron Composite	25	2.85	1000	2570	0.05	0.05	5
Al 2024-T3	126	126	961	2768			
Air	0.026	0.026	1007	1.16			
Teflon	0.252	0.252	1043	2.15			

Table 2: Parameters used during modelling

In figure 3, a thermogram with representative line profiles from the investigated panel are presented. The delamination was detected by thermography. Line profiles (on both axes) at various times from the obtained thermal images were plotted in order to obtain information about the size of the delamination in relation to the thermal transient time (e.g. possible shrinkage due to thermal diffusion). From the line profiles it was possible to calculate the size of the delamination employing the Full Width Half Maximum (FWHM) approach.

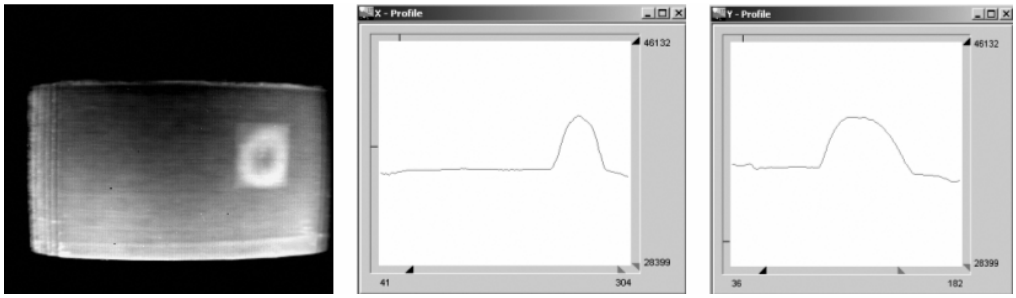


Figure 3: Thermogram and representative line profiles of the investigated composite panel

Thermal images, spatial profiles and thermal contrast curves of the panel from the thermal modelling run are presented in figure 4. The results give a good indication of how the composite material responds to thermal heating. It shows the behaviour of a delaminated composite material after it was heated with a thermal excitation source uniformly in order to detect a sub-surface defect by means of pulsed thermography.

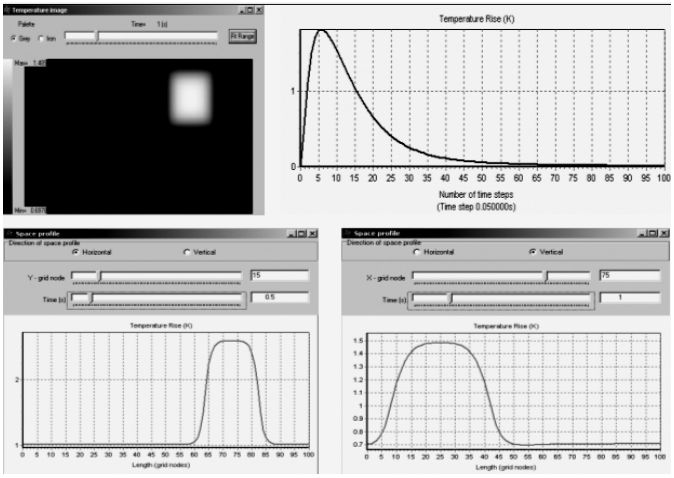


Figure 4: Thermal modelling results of composite panel. Upper graph shows development of contrast, Delta T, over defect with time. A thermal image and spatial profiles in both axes (X and Y) are also shown.

Therefore, from the obtained results it is shown that experimentally or by the use of thermal modelling it is possible to evaluate (qualitatively and quantitatively) near surface delaminations in composites.

Quality assurance and structural evaluation of GRP pipes by using PT

The Thermoscope system with the Merlin infrared camera was again utilised for the experimental treatments within this research work. A total of three samples – components were manufactured and examined using the thermography kit; in some instances due to the complexity of the investigated samples, external thermal excitation sources (i.e. hot air of 1200 Watts or optical lamp of 500 Watts) were also employed as alternative solution of active thermographic investigation. Furthermore, pulsed and pulsed phase thermography were used for evaluation of the components [4-5].
Representative thermal images of the investigated samples were obtained during the transient phase of the thermographic inspections and are presented. In some instances, plots of the contrast versus the transient time of the identified defects were performed; the difference in intensity (Δ Intensity) between the detected defect and the sound region of the sample against the transient time during the cooling down process was plotted.
Although the best possible results concerning the size of a detected defect were attained at particularly short transient times, the highest contrast images were acquired at relatively longer times.

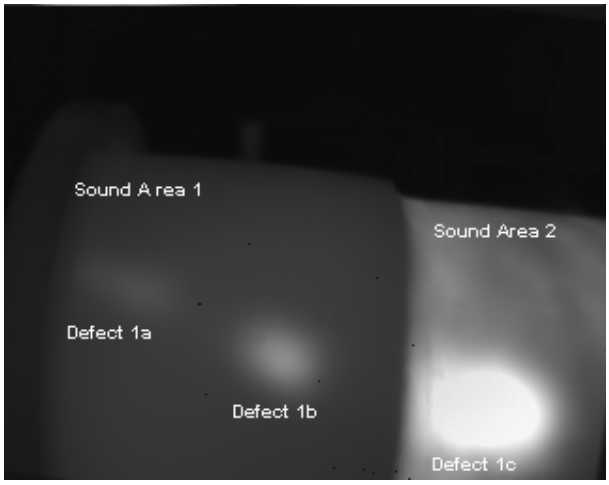


Figure 5: Thermal image of investigated pipe after 0.935 seconds of heating

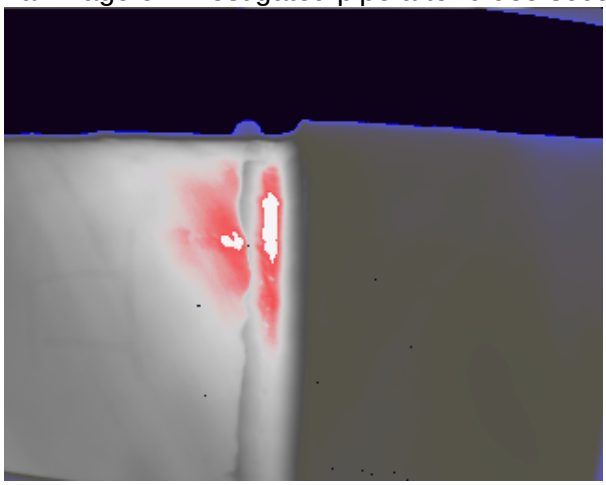
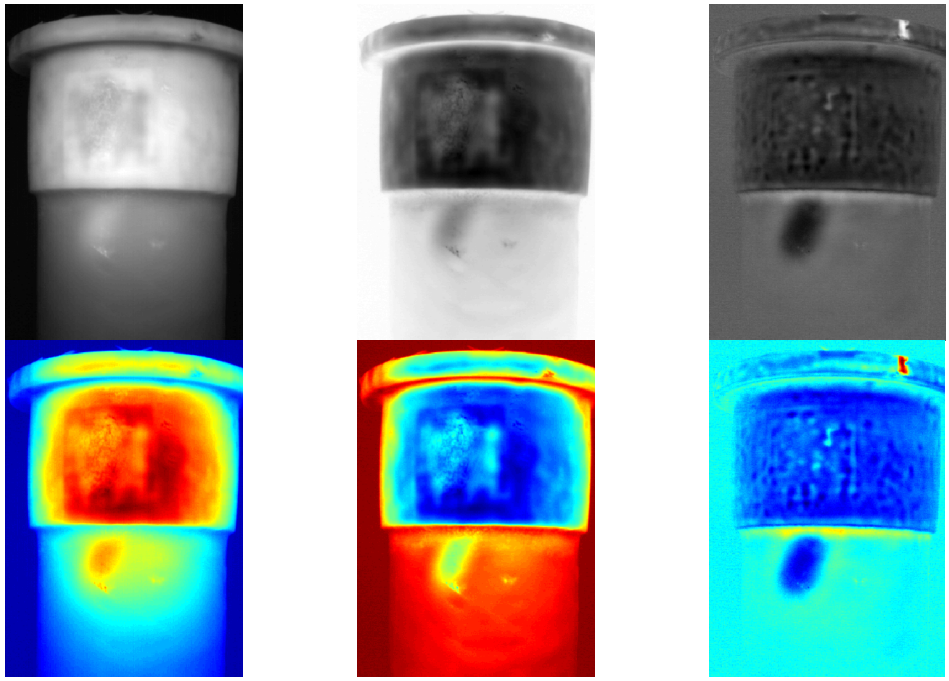
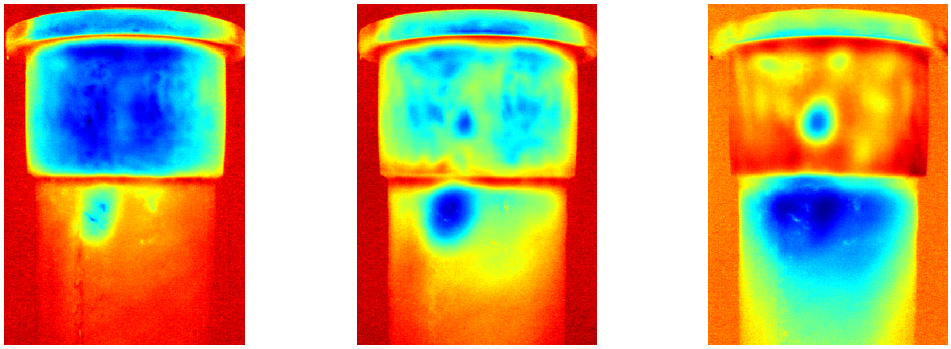


Figure 6: Thermal image of investigated pipe after 13.560 seconds of heating revealling kissing bond defect on the pipe



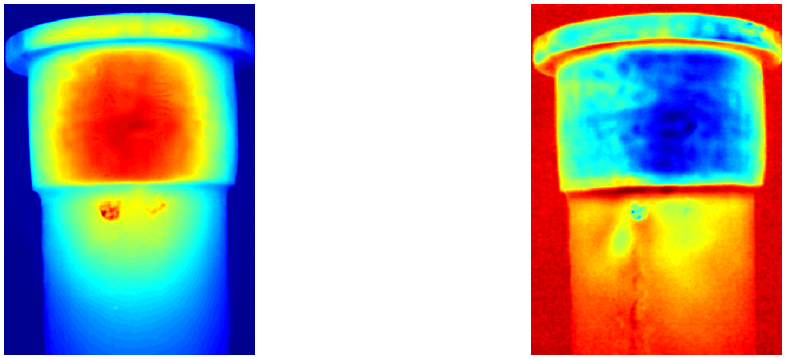
(a) (b) (c)

Figure 7: Defect ‘A’: (a) gray (top) and ‘jet’ (bottom) raw thermograms at t=0.92 s; (b) first time derivative image (from a 7th degree polynomial fitting) at t=2.85 s; (c) second derivative at t=1.49 s.



(a) (b) (c)

Figure 8: Defect ‘B’ second derivative images (from a 7th degree polynomial fitting) at t=(a) 1.26 s; (b) 3.19 s; (c) 7.51 s.



(a) (b)

Figure 9: Defect ‘C. (a) raw themogram at t=1.26 s; (b) second derivative image (from a 7th degree polynomial fitting) 2.17 s.

Since the thermal conductivity of all these three inspected samples is relatively low, the samples were tested using a reasonably low maximum frame rate. A frame rate of 15 Hz

was used; with the exception of the pipe that presented impact damage, where a higher frame rate (60 Hz) was needed. Furthermore, in order to avoid the high reflectance of the pipes during investigation and so record thermal images, the samples were either painted with black colour water based paint or even polished by applying a silver polishing substance (i.e. silvo).

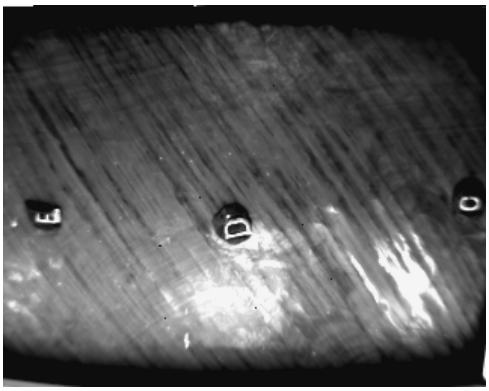


Figure 10: Thermal image of investigated impact damaged area after 0.017 seconds of heating

5. Conclusions

Transient - active thermography has emerged in recent years as a means of NDT & E technique. Its advantages are that it is a rapid large area non-contact imaging technique that produces images of subsurface features (i.e. defects) that are relatively straightforward to interpret. In this work, thermography trials took place on different components – applications. In some instances, the technique provided prompt results. Nonetheless, thermography is an inherently near surface technique whose effectiveness will decrease with the material's thickness. It also depends on the thermal properties of the material (different behaviour between high thermal conductive materials such as metals and lower thermal conductive materials such as composites).

REFERENCES

1. N.P. Avdelidis, A. Moropoulou, "Emissivity considerations in building thermography", J. Energy & Buildings 35(7), (2003), pp. 663-667.
2. N.P. Avdelidis, D.P. Almond, "Transient thermography as a through skin imaging technique for aircraft assembly: modelling & experimental results", J. Infrared Physics & Technology 45(2), (2004), pp. 103-114.
3. N.P. Avdelidis, C. Ibarra-Castanedo, X. Maldague, Z.P. Marioli-Riga, D.P. Almond, "A thermographic comparison study for the assessment of composite patches", J. Infrared Physics & Technology 45(4), (2004), pp. 291-299.
4. N.P. Avdelidis, B.C. Hawtin, D.P. Almond, "Transient thermography in the assessment of defects of aircraft composites", J. NDT & E International 36(6), (2003), pp. 433-439.
5. C. Ibarra-Castanedo, N.P. Avdelidis, E.G. Grinzato, P.G. Bison, S. Marinetti, L. Chen, M. Genest, X. Maldague, "Quantitative inspection of non-planar composite specimens by pulsed phase thermography" J. QIRT 3(1), (2006), pp. 25-40.