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Invited paper

Pulsed thermography: philosophy, qualitative & quantitative analysis on aircraft materials & applications

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Abstract

Thermal non-destructive testing (NDT) is commonly used for assessing aircraft structures. This research work evaluates the potential of pulsed thermography (PT) for certain applications. In particular, real time monitoring was obtained using PT. In some cases, thermal modelling as well as other non-destructive testing and evaluation techniques (i.e. acoustography, ultrasonic wheel array) were also used with the intention of providing supplementary results. The following features were studied and presented:

- Through skin sensing on aluminium (Al) alloy and carbon fibre reinforced plastic (CFRP) structures.
- Defect detection under multi-ply composite repairs.
- Impact damage on carbon fibre reinforced plastic panels and honeycomb sandwich structures.
- Drilling induced defects on multi-ply laminates of carbon fibre composites.

It is concluded that PT is a rapid large area non-destructive technique that can find adequate use on aircraft – aerospace materials and structures.

Keywords: pulsed thermography, NDT, aircraft, defect detection, quantitative assessment, through skin sensing.

1. Theoretical Background on Thermal NDT

Infrared - thermal investigation techniques have been used successfully in several of applications, i.e. inspection of subsurface defects and features, identification of thermo-physical properties, detection of coating thickness and hidden structures [1]. There are two approaches that can be used: passive [2] and active [3]. The passive approach is commonly used in the investigation of materials that are at different temperature (regularly higher) than ambient, whilst in the case of the active approach a thermal excitation source is employed with the intention of inducing thermal contrasts [4].

In the active approach of the thermal NDT, pulsed thermography (PT) is a widely used approach for investigating aircraft materials and structures. PT is a popular thermal stimulation technique where the surface under investigation is pulse heated (time period of heating varying from a few milliseconds for high conductive materials such as metals to a few seconds for low conductive materials such as composites) using one or more pulse heating sources and the resulting thermal transient at the surface is monitored using a thermal camera [5].

In the 1980's, Vavilov and Taylor [6] discussed the principles of thermal NDT expressing the ability to provide quantitative information about hidden defects or features in a material. Although thermal NDT

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has the potential to deliver first class results, there are various properties of the material(s) that need to be considered:

- Thermal Properties: conductivity, diffusivity, effusivity, specific heat.
- Spectral Properties: emissivity, absorption, reflection, transmission.
- Other Properties - Characteristics: density, porosity.

All of the above mentioned features are very important when dealing with thermal NDT surveys. For example, when a material presents voids or pores in its structure [7], then its thermal conductivity and density decreases, its thermal diffusivity is altered and so the conduction of heat transfer within the material is affected [8]. This can be realised from the following equation:

$$a = \frac{k}{\rho C_p} \qquad (1)$$

where:
α is the thermal diffusivity (m^2s^{-1}), k is the thermal conductivity ($Wm^{-1}K^{-1}$), ρ is the density (kgm^{-3}) and Cp is the specific heat capacity ($Jkg^{-1}K^{-1}$).

Another consideration when a thermal NDT survey is to be completed is the thermal effusivity of the materials to be tested. Materials with low effusivity values will present higher temperatures, since:

$$T = \frac{Q}{e\sqrt{\pi t}} \qquad (2)$$

where:
Q is the input energy (Joules) and e is the thermal effusivity ($Ws^{1/2}m^{-2}K^{-1}$), which can be calculated by:

$$e = \sqrt{k\rho C_p} \qquad (3)$$

where:
k is the thermal conductivity ($Wm^{-1}K^{-1}$), ρ is the density (kgm^{-3}) and Cp is the specific heat capacity ($Jkg^{-1}K^{-1}$).

Following the early work of Vavilov and Taylor, thermal NDT has been implemented by several groups worldwide [7-11]. Thus, the potential of the technique for detecting and imaging subsurface defects have been greatly enhanced and the defect imaging process is now well understood [12].

2. Through skin sensing

The objective of this work was to study the ability of PT for locating anchoring points beneath the outer skin of aircraft structures, to facilitate automated drilling and fixing. Typical test structures, comprising of either Al or CFRP aircraft skin positioned over a thick Al and/or 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 [13].

The representative test structures, comprising an Al aircraft skin (1.6mm) positioned over a thick Al strut and of CFRP skin (2mm or 4mm) over a thick CFRP strut, were analysed using the ThermoCalc-3D software. The dimensions of all investigated panels were 500 x 500 mm. 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 (the 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).

The following remarks can be made from the modelling results:

- The peak contrast of 4mm CFRP skin over CFRP strut is 2 times smaller than that of 2mm CFRP skin over CFRP strut, whilst its time scale (thermal transient phase) is 4 times longer.
- The 4mm CFRP skin over the CFRP strut presents the lowest thermal contrast amongst the tested modelled structures, while its time scale (thermal transient phase) is the longest (i.e. 20 seconds).
- The peak contrast value of Al is approximately 4.65 times greater than that of the CFRP (2mm skin), for zero air gap, since the differences of the Peak ΔT values are 0.05028 K for the Al and 0.0108 K for the CFRP.

For the experimental work, an integrated pulsed thermographic system (Thermoscope) employing a medium wave infrared camera (Merlin 3-5 μm by Indigo) was utilised. The non-destructive evaluation system has an integrated flash heating system with a power output of 2KJ in 2 to 5 ms. The infrared camera uses a cooled indium antimonide detector with a frame rate of 60 Hz and a focal plane array pixel format of 320 (H) x 256 (V). The same panels, similar to thermal modelling, were investigated. 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 (a line was marked on the skin surface to show the centre line of the strut).

In the Al case, since the thermal conductivity is exceptionally high, the maximum frame rate (59.88 frames per second) was used for the recording of the images. In order to avoid the high reflectance of Al during investigation and to record thermal images, the sample was painted with a water based black paint. Furthermore, in order to reduce the thermal contact resistance (air gap) that it is formed between the two surfaces (skin and strut) it was necessary to apply a load between the panel and the strut. In the first instance, bending the strut to form a low curvature fixing and wrapping the skin over it achieved this (two bending positions of 2.5 cm and 5 cm were studied). In the second instance, the panel was examined at various loadings – pressures.

In contrast to the work on Al parts, it was found that the thin CFRP skin (i.e. 2mm) over the CFRP strut could be imaged satisfactorily without significant loading. In the case of the 4mm CFRP skin over the CFRP strut various pressures were applied (similar way to the Al case). In addition, due to the relatively low thermal conductivity of the CFRP material the thermal images during the cooling down process were acquired with a frame rate of 7.49 frames per second (for the 2mm skin) and 3.75 frames per second (for the 4mm skin).

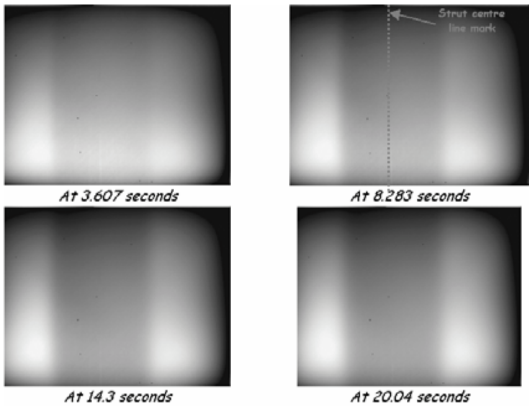

Figure 1: a selection of thermal images showing the strut beneath the 2mm CFRP skin

Furthermore, in all cases, 5 line profiles along the X-axis at 20, 74, 128, 182 and 236 (Y pixel values) were taken in order to define the centre of the strut using the FWHM (Full Width Half Maximum) approach.

In this part, the characteristics of thermal images for the assessment of under skin structures of different skin thickness were investigated through modelling, as well as experimentally. PT showed that can be used effectively in the detection of subsurface features located beneath relative thin skins (i.e. up to 4mm). In addition, it showed great potential as far as locating the centre of a substrate accurately. The accuracy of centre line of the subsurface struts for both studied cases was better than 1 pixel (i.e. less than 0.5 mm). This is the limit imposed by the field of view and pixels of the infrared camera (320 x 256).

3. Defect detection under multi-ply composite repairs

In PT, the qualitative thermal images can be translated into quantitative results by analysing the time and spatial dependency of the surface temperature. Thus, information concerning the size of a detected defect can be achieved. However, PT is an inherently near surface technique whose effectiveness decreases with defect depth and it is also dependent on the thermal properties of the investigated material.

In this part, a composite repair patch [14] 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 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 the Thermoscope system with the same set-up configuration as in the previous section. For the purposes of thermal modelling, the ThermoCalc-3D software was employed.

In figure 2, 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 delamination (figure 3) employing the FWHM approach.

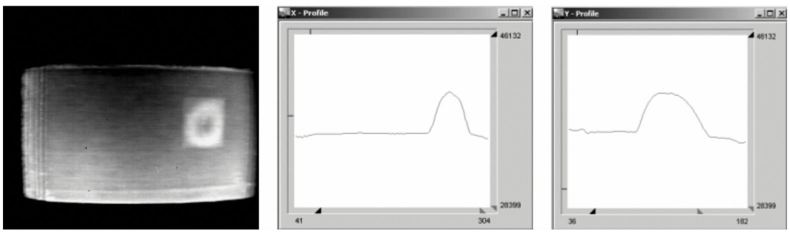

Figure 2: thermogram and representative line profiles of the investigated composite panel

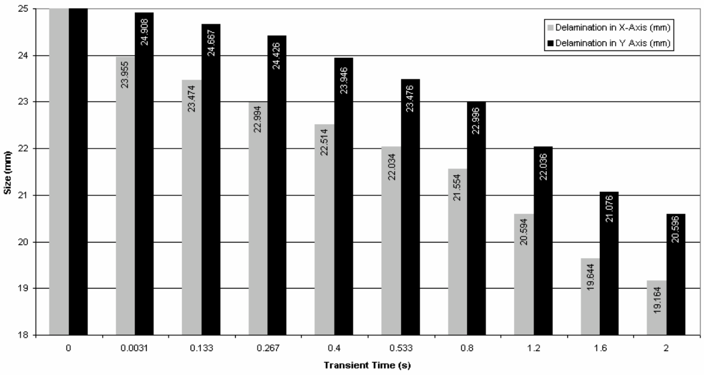

Figure 3: Size –vs- thermal transient time graph of delamination in composite patch.

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 PT.

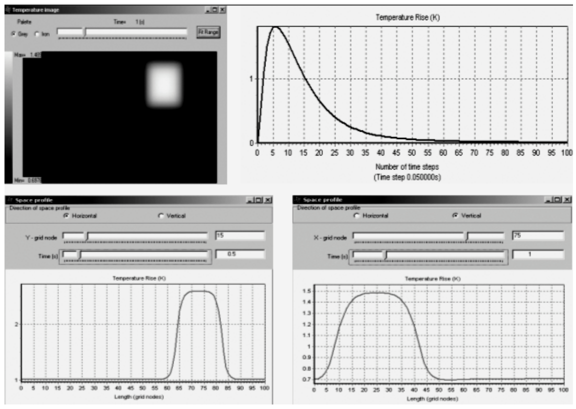

Figure 4: thermal modelling results of composite panel. Upper graph shows development of contrast, Delta T, over defect with time. A thermal image and spatial profiles in both axes (X and Y) are also shown.

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.

4. Impact damage on CFRP panels and honeycomb sandwich structures

Damage caused by low velocity impacts is a particular concern in the aircraft industry. In this work, impact damaged CFRP panels (150 x 100mm) of 2mm thickness (16 ply with a quasi-isotropic lay-up), as well as sandwich composite samples formed after bonded to the two faces of 25 mm thick Type 6 Nomax honeycomb core were investigated. All panels were cut from the same sheet. A falling weight impactor with a hemispherical 12.5 mm radius head was used to apply impacts of controlled energy. During impact, the samples were supported around their edges over a 125 x 75 mm aperture, allowing the bulk of the panels to rebound freely on impact. The Thermoscope pulsed transient thermographic system, employing the medium wave infrared camera (Merlin 3-5 μm by Indigo), was used to image the impact damage [15].

PT is a rapid large area technique with the additional advantages of being single-sided and non-contact. These attributes make this technique particularly suitable for surveying either single panel or sandwich structures for impact damage. Examples of thermography images impact damage in the two types of samples are shown in figure 5.

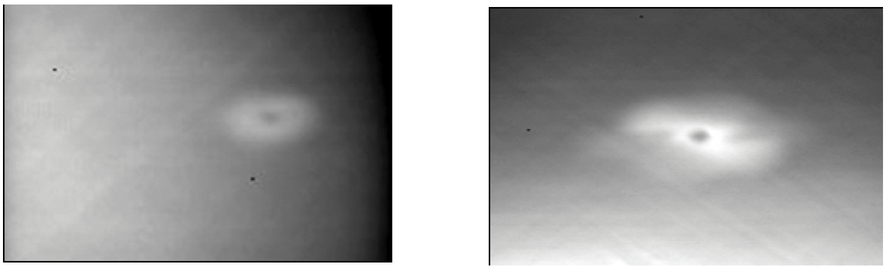

Figure 5: thermal images of 12.75J impact damage in a panel sample (left) & in a sandwich sample (right) taken 0.5s after flash heating.

In addition to the evident difference in defect size, the sandwich sample image contains a high contrast component caused by a delamination close to the surface. A comparison of contrast vs. elapsed time for the two images shows contrast peaking at a much earlier time for the sandwich sample, consistent with delaminations close to the surface.

The size and the through thickness characteristics of the impact damage produced in single panel and sandwich samples are reflected in the NDT images obtained by PT. The technique has been shown to be effective for detecting and imaging impact damage in either isolated panel or sandwich samples.

5. Drilling induced defects on multi-ply laminates of carbon fibre composites

An area where relatively little work has been done is on the criticality of defects formed during either manufacturing or assembling of aircraft composites. There are quite a few defects that can occur within composites both due to the manufacturing of the material and subsequent handling and assembly of manufactured components. Such defects can reduce the mechanical performance of the structure and thus must be studied. Knowledge of defects, their detection and their importance is important in cutting manufacturing costs and thus it is of particular significance to the aerospace industry.

In this work, multi-ply laminates of HEXCEL AS4/8552 carbon fibre composites containing drilling induced defects were examined [4]. 4mm thick laminates that were produced by the lay-up of 16 plies of UD-prepreg tape in a predetermined sequence were tested. The lay-up sequence was a quasi-isotropic (25/50/25) laminate with a stacking sequence of: [(45,0,-45,90)2]s.

Various assembly defects were introduced to the CFRP panels using specific drilling parameters, i.e. spindle speed, feed rate, clamping and backing. The defects were all associated with the drilling of holes within composite panels. PT, one of the latest non-destructive techniques used effectively for the assessment of aircraft materials, was employed in the imaging of the artificially created defects. In particular, the following assembly related types of defects were investigated:

- Overtorqued fasteners: through thickness crushing of material due to loads imposed by the fastener.
- Burned drilled holes: localised damage in region of drilled hole caused by frictional heating of drill bit.
- Mislocated – podged holes: holes produced in incorrect location for fastener.
- Over-countersunk holes: countersink drilled at incorrect angle.

PT was carried out to evaluate the quality around the drilled hole, as well as the defect size. The Thermoscope pulsed thermographic system employing the medium wave (3 – 5 μm) infrared camera (Indigo) was used for the imaging of the defected samples. The pulsed thermographic investigation was made of the dependence of defect image contrast and of thermal properties of the tested materials.

The overtorqued fasteners' defects might arise at any section on a CFRP panel where bolts are used to fasten together two components. This overtorquing of fasteners can result in damage to the composite in the region local to the bolt-hole through the thickness of the laminate. The extent and severity of a defect is greatly dependent on the loads induced through the thickness of the examined composites.

Figure 6a, shows a minor defect within the investigated panel. The drilled hole can be seen as a dark circular region (lower temperature) in the centre of the thermal image. A very thin bright grey area (higher temperature) can just be seen around the drilled hole, indicating the presence of a defect. Figure 6b displays the thermal image of the panel enclosing a typical defect. Although the thermal image appears to be analogous to that of figure 6a, nonetheless, the hot area around the drilled hole is slightly more distinctive, suggesting greater damage in the form of matrix cracking and/or delaminations. Figure 6c displays the severe crushed material defect. The damage region appears to spread further from the edge of the hole and looks to be more severe. Nonetheless, the damage does not seem to be continual around the perimeter of the drilled hole and that the area adjacent to the drilled hole appears to be defect free.

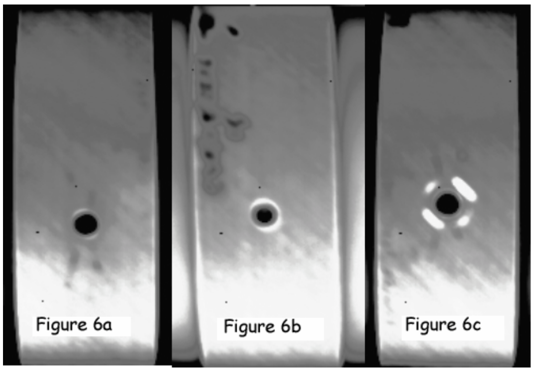

Figure 6: Thermal Images of samples with overtorqued fasteners' defects.

The burned drilled holes' defect, which is a result of the localised frictional heating between the drill bit and the composite material, was also investigated. This type of defect can be detected macroscopically within the drilled hole and is likely to exist throughout the thickness of the material, being most severe towards the through thickness centre of the laminate. Similarly, the acquired thermal images indicated the extent of the damage on the investigated panels.

The mislocated - podged holes' defect occurs in assemblies where several fasteners are utilised to attach a component in place. Several times, the misalignment of the drilled hole is considerably great that makes it impossible for the fastener to be inserted; podging of such holes involves inserting an object, i.e. screwdriver, into the misaligned hole and levering the holes into position. In CFRP, such process has the potential to induce severe damage in and around the drilled hole. PT was used effectively to obtain information on the extent of damage due to podged holes.

The use of countersunk bolts is common within aircraft applications. However, a number of different defects can occur when drilling countersunk holes, i.e. countersunk hole is drilled too deep causing the bolt head to sink below the aerodynamic surface of the component. Moreover, an overcountersunk hole is not easily repaired and since countersinking removes material from around the hole, such defects can potentially be detrimental to the mechanical performance of the component. PT was competent in the detection of overcountersunk holes.

6. Conclusions

The main objective of this work was to study the effectiveness of PT to assess various defects and or features on representative aerospace materials. The technique provided excellent results in all cases. The advantages of the technique are that it investigates rapidly large areas for surface or near surface defects and that it generates interpretable results. Nonetheless, a major disadvantage is that its success is highly dependent on defect depth and size, which restricts its application to near surface defect imaging.

7. Acknowledgements

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