Thermal NDT of Composites in the Aero Space Industry: A Quantitative Approach

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Abstract
Thermal inspection has become a recognized NDT tool in the aero space; however, practical surveys still remain rather qualitative. This is conditioned by a lack of basic research aiming to establish quantitative relationships between defect severity and chosen decision making parameters. Therefore, an evident modern trend in thermal NDT is the data processing in the time/phase domains where many noise factors can be considerably subdued. In this study, the emphasis is made on the development of two types of quantitative thermal NDT techniques: mapping thermal inertia (one-sided procedure) and thermal diffusivity (two-sided procedure).

Keywords: Thermal nondestructive testing, infrared thermography, effusivity, diffusivity, aviation materials

1. Introduction

The proportion of composites (composite structural weight) used on the civil air fleet has been increasing exponentially since the 1970s to reach about 50% on the B787, A350 aircraft. In the military, this figure has nearly reached the physical limit with over 82% of fuselage panels being manufactured of composites. Respectively, the number of material breakdowns related to composites is currently about 50%. Composites are characterized by some typical defects that may appear during both production and exploitation, or repair. These are delaminations and disbonds (at the stage of manufacturing), burns as a result of inadequate hot curing and low-quality patches as an undesirable result of in-service repairs, and water ingress sites and impact damages that appear during exploitation. Therefore, in aviation, the maintenance strategy involves manufacturing reworks, health check and in-service repairs. In all these cases, a role of nondestructive testing (NDT) cannot be underestimated. Thermal inspection has become a recognized NDT tool in the aero space; however, it looks that only in the space industry this technique acquires some quantitative features, merely to mention the investigation of the “Colombia” space shuttle catastrophe occurred in 2003. In aviation, practical surveys still remain rather qualitative. This is conditioned by a lack of basic research aiming to establish quantitative relationships between defect severity and chosen decision making parameters. It is worth noting that the temperature itself is a fairly vulnerable parameter subjected to many noisy factors, first of all, uneven heating. Therefore, an evident contemporary trend in thermal NDT (TNDT) is the data processing in the time/phase domains where many noisy factors can be considerably suppressed. In this study, the emphasis is made on the development of two types of quantitative TNDT techniques: mapping thermal inertia (one-sided procedure) and thermal diffusivity (two-sided procedure).

2. Short historical notes

Within the US X-33 launch vehicle program, it has been demonstrated that TNDT has proven to be a very efficient method due to the following reasons [1]: 1) TNDT scan rate is much higher than that of the ultrasonic method, 2) TNDT inspection cost is less than that of ultrasonics, 3) TNDT could be performed in the factory area where the parts were fabricated, making unnecessary to move the parts to the ultrasonic test laboratory, 4) the commonly-used ultrasonic inspection exposes the CFRP facesheet to water, which permeates the surface and becomes trapped inside the panel; TNDT is able to verify the removal of the water, 5) location
of defects detected by TNDT could easily be marked on the surface of the parts, and 6) TNDT is able to find defects that have not been detected by ultrasonics.

Even if the X-33 program has been recently curtailed, it is assumed that IR thermographic inspection can be undoubtedly used in any program on the development of new space techniques.

A new impetus for a wider use of TNDT in the US space shuttle program was done by the conclusion of the commission which investigated the Columbia catastrophe occurred in 2003. It was stated that a piece of the cork-like thermal insulation which torn off during the launch hit the shuttle under the left wing that was recorded by the launch video. A lack of an appropriate repair technology and the underestimation of the severity of the incident led to the catastrophe during the re-entry.

A commercial TNDT system was used for inspecting wing leading edges of the Discovery space shuttle after its mission in August 2005. A defect indication was found to be further confirmed as the deterioration of the RCC composite structural integrity.

A parallel research has been related to the implementation of IR thermography as a tool for performing active or active/passive NDT in the outer space [2]. The strategy of the orbital NDT assumes that if an Orbiter Boom Sensor System (OBSS), which includes a video camera and two lasers, will detect damage of the shuttle skin, the team should perform a more detailed survey by using a digital video camera of high resolution, as well as an IR imager. The survey purpose would be the evaluation of composite damage size and severity that should result in decision to either continue the mission or perform repair.

In Russia, according to some fragmentary information, TNDT is being used in the program on the development of a Clipper (now Rus) space shuttle.

The Boeing and Airbus corporations broaden the use if TNDT because this technique meets many requirements to a best candidate NDT technique which have been formulated by the Nordam company in the following form [3]: 1) a method should detect defect of different types, such as oil/water intrusion, delaminations, corrosion, disbonds etc.), 2) a method should scan the panel surface and possibly produce an image, 3) a method should not require extracting a test object out of an airplane or its considerable disassembling, 4) inspection results should be evaluated on test site, 5) inspection results should be well documented and archived for future reference, 6) test equipment should be portable and mounted in a short time, 7) test equipment should be convenient for using by Level I thermographers, 8) implementation of test equipment should not cause essential re-organization of already operating inspection system.

Large areas eligible for NDT on aircraft and rockets, as well as a high cost of aero space technique, make a compromise between the NDT sensitivity and inspection speed particularly important. In this aspect, aviation applications of IR thermography seem to be very appropriate. For example, the US aero space industry represents a major marketplace for active TNDT systems. In the last decade, the Thermal Wave Imaging (TWI), Ltd. became known for its successful developments in the field of transient TNDT, merely to mention the ThermoScope and EchoTherm units. These units realize a patented technology of the Synthetic Thermographic Signal Processing (STSP). The STSP technology includes pulsed heating of a test object, capturing an image sequence with an IR imager of a larger format and high sensitivity, presenting experimental data in the Log-Log format, polynomial data fitting and, finally, producing maps of characteristic heat transit times. One of the last achievements of this company is the development of the MOSAIQ software which allows the synthesis of large-scale IR images of extended test objects, such as airplane fuselage, by combining numerous single IR thermograms.
2. Qualitative evaluation of defect detection

2.1 Defect detection parameters

Defect detection is performed by an operator or an automatic device. Operators are guided by some heuristic rules which are not well understood even if it is clear that pixel amplitudes, defect pattern size and shape are crucial in decision making.

The heuristic approach to qualitative defect detection can be illustrated with the so-called Tanimoto criterion [4]:

\[ TC = \frac{N_{r.d} - N_{m.d.}}{N_{r.d} - N_{f.d.}}, \]  

(1)

where \( N_{r.d} \), \( N_{m.d.} \), \( N_{f.d.} \) are the numbers of true, missed and false defects detected by the operator in an image. The interesting feature of the Tanimoto criterion is that it combines missed and false defects. Note that \( TC \) becomes equal to 100% only if the probability of correct detection \( P_{c.d.} = 100\% \) and the probability of false alarm \( P_{f.a.} = 0 \). This criterion can be used in the comparison of various NDT methods and processing algorithms by analyzing reference samples with \textit{a priori} known defects.

For example, the Tanimoto criterion was used in processing results of one-sided TNDT of a carbon fiber reinforced polymer (CFRP) specimen which contained nine Teflon inserts by size 3\( \times \)3, 6\( \times \)6 and 12\( \times \)12 mm placed at the depths of 0.25, 1.25 and 2.5 mm. The statistical results averaged by eleven operators are presented in Table 1 along with the data standard deviations \( \sigma_{TC} \).

The following conclusions were made: 1) unlike commonly believed, the number of false defects was little that can be explained by the regular displacement of the defects in the specimen, 2) various forms of data graphical presentation (color, B & W and their copies) did not influence the efficiency of defect detection, and 3) the highest \( TC \) values corresponded to the so-called timegram that is a result of data treatment by applying the algorithm of dynamic thermal tomography.

<table>
<thead>
<tr>
<th>Image description</th>
<th>( TC ), %</th>
<th>( \sigma_{TC} ), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source IR image</td>
<td>8.9</td>
<td>3.41</td>
</tr>
<tr>
<td>Source IR image after histogram equalization (color)</td>
<td>52.2</td>
<td>1.6</td>
</tr>
<tr>
<td>Source IR image after histogram equalization (B &amp; W)</td>
<td>57.8</td>
<td>1.4</td>
</tr>
<tr>
<td>Source IR image after histogram equalization (B &amp; W copy)</td>
<td>44.4</td>
<td>0</td>
</tr>
<tr>
<td>After normalization by end of heating*</td>
<td>63.3</td>
<td>3.2</td>
</tr>
<tr>
<td>Timegram*</td>
<td>65.6</td>
<td>1.1</td>
</tr>
</tbody>
</table>

*Normalized images and timegrams are the results of special data treatment [4, 5].

Visual perception of infrared (IR) thermograms is related to a signal-to-noise ratio in its simplest form:

\[ S = \frac{\left( \sum_{i=1}^{M} T_i - \overline{T}_{nd} \right) / M}{\sigma_{nd}}, \]  

(2)
where $T_i$ is the temperature (or any derivative signal) in the $i$-th pixel of a defect area, $\bar{T}_{nd}$ is the mean temperature in a non-defect area, $\sigma_{nd}$ is the temperature standard deviation in a non-defect area, and $M$ is the number of pixels in a chosen defect area. Equation (2) can be efficiently applied to temperature distributions where defect areas are characterized by higher or lower temperatures in regard to the non-defect background. However, the use of some data processing algorithms, such as the Fourier and wavelet transforms, principle component analysis (PCA) [4, 6, 7], etc., may result in specific signal patterns over hidden defects where signal amplitudes can be simultaneously higher and lower than the background. In this case, the following formula is recommended:

$$S = \frac{\sum_{i=1}^{M} |T_i - \bar{T}_{nd}| / M}{\sigma_{nd}}. \quad (3)$$

In the case of automatic devices, the simplest algorithm involves the establishment of a signal threshold $U$ with a differential temperature signal or some derivative parameters being served as decision making parameters. If such parameters are subject to the normal distribution, the theory of statistical decisions provides the following expressions for determining the probability of correct detection $P_{c.d.}$ and false alarm $P_{f.a.}$:

$$P_{c.d.} = 1 - \Phi \left( \frac{\bar{U}_d - U_{thr}}{\sigma_{nd}} \right);$$
$$P_{f.a.} = \Phi \left( \frac{U_{thr} - \bar{U}_{nd}}{\sigma_{nd}} \right), \quad (4)$$

where $\Phi (Z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-x^2/2} dx$ is the tabulated Laplace integral, $\bar{U}_d, \bar{U}_{nd}$ are the signal mean values in the non-defect and defect areas respectively, and $U_{thr}$ is the threshold value. For example, to obtain $P_{f.a.} = 5\%$ one has to set the decision making threshold equal to $\bar{U}_{nd} + 1.6 \sigma_{nd}$.

### 2.2 Experimental setup and image evaluation

Experimental results presented below have been obtained on an IR thermographic set-up at Tomsk Polytechnic University which includes: 1) heat sources of different types: optical, inductive and ultrasonic, 2) FLIR SC 7700M and NEC Avio TH-9100 IR imagers, 3) modeling and data processing software. In this study, only a flash heater consisted of 2 Xenon flash tubes (total flash energy 3.2 kJ, pulse duration about 5 ms, energy absorbed by samples $Q=12700$ W/m$^2$) was used. Typically, the image sequences analyzed with the home-made ThermoLab software included 200-300 IR thermograms of the format 320x240.

An example of TNDT of a 4.6 mm-thick CFRP sample which contained a 46 J impact damage (such defects frequently appear on aircraft under exploitation due to hailing, bird and luggage strikes, etc.) is given in Figure 1. On the sample front surface where the impact occurred, only the minor ‘footprint’ of the defect is seen (Figure 1a, while the major defect section takes place close to the rear surface (Figure 1f). According to Equation (3), the
maximum $S$ values appear when applying the correlation technique. We remind that this technique is based on the calculation of a correlation coefficient between all pixels and a pixel chosen as a reference. The correlation algorithm often provides a uniform background with the correlation coefficient very close to one and close to zero dispersion thus significantly enhancing $S$.

\[ S = 12.1 \]
\[ S = 17.1 \]
\[ S = 72.5 \]
\[ S = 9.2 \]
\[ S = 10.3 \]
\[ S = 140.2 \]
\[ S = 271.1 \]
\[ S = 3383.0 \]
\[ S = 145.3 \]
\[ S = 425.8 \]

Figure 1. Evaluating 46 J impact damage in 4.6 mm-thick CFRP sample (one-sided test, front surface: a-e; one-sided test, rear surface: f-k):

- a, f – optimal source images,
- b, g – Fourier phasegrams,
- c, h – correlogram,
- d, i – PCA image,
- e, k – complex wavelet phasegram

3. Effusivity and diffusivity as the parameters of defect severity

3.1 Effusivity

There were some attempts to apply non-temperature parameters, such as Fourier phase, polynomial coefficients, etc. to defect characterization [4, 6], however, a lack of a clear physical content makes their use difficult in the evaluation of defect severity. It seems more convenient to use material thermal properties to characterize 'defectivity' of materials and components.

Effusivity $e = \sqrt{KC\rho}$ (K is the thermal conductivity, $C$ is the specific heat, $\rho$ is the density) comes from the known solution for heating an adiabatic semi-infinite body with a Dirac pulse:

\[ e = \frac{W}{T^F(\tau)\sqrt{\pi \tau}} \quad (5) \]

where $T^F$ is the front-surface temperature, and $W$ is the absorbed energy. Equation (5) can be applied to experimental $T(\tau)$ evolutions to calculate apparent effusivity. In the ideal case of a semi-infinite adiabatic body heated with a Dirac pulse the plot of a $e(\tau)/W$ dependence represents a horizontal line. In practical cases (non-adiabatic sample of finite thickness, a heat pulse of finite duration, heater residual radiation) experimental curves are not so simple. An analytical illustration is given in Figure 2a,b for a three-layer CFRP plate (see 1D model parameters in the legend, note that $W = Q\tau_0$). It is clearly seen that, over the defect area, the minimum $e/W = 0.069 \ \text{°C}^{-1} \cdot \text{s}^{-1/2}$ occurs at 1.29 s. Respectively, the
The minimum relative variation of effusivity $e_{rel} = e_d/e_{nd} - 1$ is -30.9% at 1.57 s. It is worth noting that $e_{rel}$ can be calculated via the running contrast $C = (T_d/T_{nd} - 1)$ often used in the TN model: $e_{rel} = -C/(1+C)$, and extremum values of both $e_{rel}$ and $C$ occur at the same time.

![Figure 2](image.png)

Figure 2. Effusivity concept in TNDT (analytical model of an 1D air-filled defect in CFRP: $Q=10^5$ W/m², $\tau_h=10$ ms, $L=5$ mm, $l=0.5$ mm, $d=0.1$ mm, CFRP - $K=0.57$ W/(m·°C), $a=3.16 \times 10^{-7}$ m²/s, air - $K=0.07$ W/(m·°C), $a=5.8 \times 10^{-5}$ m²/s):

a – 1D model and apparent diffusivity vs. time (analytical solution),
b – $e_{rel}$ vs. time (analytical solution),
c – apparent diffusivity vs. time (experimental results, 1.6 mm-thick CFRP sample, 17.9 J impact damage)

The experimental data is shown in Figure 2c for a 1.6 mm-thick CFRP sample which contains a 17.9 J impact damage (apparent effusivity is determined by applying the one-sided test procedure to the rear surface). Qualitatively, the profiles in Figure 2a and 2c are similar, and
the constant effusivity decay in Figure 2c can be explained by the presence of the residual radiation emitted by the Xenon bulb balloons. Effusivity is a natural material parameter that characterizes practically-interesting one-sided TNDT procedures. However, since $e \sim 1/T^F$, the effusivity parameter is susceptible to noise, same as temperature.

Figure 3a shows the best source image of the above-mentioned CFRP sample, and the three images of Figure 3b illustrate how effusivity is evolving in time. The best defect visibility is provided by the effusivity image at about 2 s that corresponds to the minimum in the respective curve in Figure 2c: the $e/W$ value drops down to 0.0343 °C⁻¹.s⁻¹/² to compare to the non-defect value of 0.172 °C⁻¹.s⁻¹/², i.e. the relative effusivity variation is $\Delta e/e_{nd} = -80\%$.

![Figure 3](image)

**Figure 3.** Effusivity concept illustration in one-sided inspection of 1.6 mm-thick CFRP sample with 17.9 J impact damage:

a – best source image,
b – apparent effusivity images (from left to right: $\tau = 0.3, 2, 20$ s)

### 3.2 Diffusivity

Two-sided TNDT procedures involve heat conduction solutions for rear surface of samples under test. In this case, diffusivity $a$ appears as the first-order parameter. The temperature on the surface of an adiabatic plate heated on the opposite surface with a Dirac pulse is:

$$T^R = (Wa/KL) \left(1 + 2 \sum_{n=1}^{\infty} (-1)^n e^{-n^2\pi^2Fo} \right),$$

where the superscript «$R$» specifies a rear surface, $Fo = a\tau/L^2$ is the Fourier number, and $L$ is the plate thickness.

The determination of material diffusivity represents an important research area. The use of IR thermography allows mapping this parameter with its variation $\Delta a/a$ being an indicator of material 'defectivity'. Unlike effusivity, the $a$ parameter is independent of absorbed energy thus being more noise-resistant.

The corresponding illustration is given in Figure 4 for the same CFRP sample as in Figure 2c (two-sided TNDT procedure). The rear-surface temperature profiles of Figure 4a allow the determination of diffusivity by the classic Parker's formula: $a = 0.139L^2/\tau_{1/2}$, where $\tau_{1/2}$ is the so-called half-rise time. The processing of pixel profiles, such as shown in Figure 4a, results in the pair of images called «halfgram» $T(i, j, \tau_{1/2})$ and «timehalfgram» $\tau_{1/2}(i, j)$. The halfgram in Figure 4b shows a vague indication of the impact damage because the temperature rise on the rear surface did not exceed 1.2-1.6 °C, however, the time-domain image (timehalfgram) in Figure 4c seems to be noise-free thus allowing a high-quality map of diffusivity (Figure 4d) obtained by the Parker formula. It is seen that in the defect area the
diffusivity value drops from $4.2 \times 10^{-7}$ to $1.1 \times 10^{-7}$ m$^2$/s, i.e. the relative diffusivity variation in this case is $(a_d/a_{nd} - 1) = \Delta a/a_{nd} = 74\%$. Note that below the negative sign of both $\Delta e/e_{nd}$ and $\Delta a/a_{nd}$ will be omitted.

It would be appropriate to deal with diffusivity in a one-sided procedure but this requires performing some manipulations with a front-surface temperature signal, for example, by introducing the following function:

$$T' = F_0^n T_D^F,$$

which reaches minimum at a particular time $F_{0_{\text{min}}}$ (here «$D$» specifies a Dirac pulse, and $n=0\mathrm{--}1$). The use of this approach in TNDT needs further exploration.

$T$, °C

![Graphs and images](image)

Figure 4. Determining diffusivity of a 1.6 mm-thick CFRP sample with 17.9 J impact damage (see Figure 2c):

- a – temperature vs. time,
- b – IR thermogram at $\tau_{1/2}$ («halfgram»),
- c – image of $\tau_{1/2}$ («timehalfgram»),
- d – diffusivity map

4. Effusivity & diffusivity vs. impact damage energy

Eight CFRP samples with the thickness from 1.6 to 4.8 mm which contained impact damage defects of different energy were inspected by applying both a one- and two-sided procedures. The samples were impacted on the front surface where composite damage was hardly visible, and the temperature distribution was thermographically monitored on both surfaces. The
results are presented in Table 2 and in Figure 5 for seven energy values because one extreme point (in Italic in Table 2) was excluded from the consideration. It is seen that relative effusivity variations are higher than variations in diffusivity that can be explained with the fact that all defects were located closer to the rear surface where the heating was applied in a one-sided procedure. By other words, effusivity values strongly depend on defect depth while diffusivity values remain the same and are independent on whether a front or rear sample surface is heated. Besides, the variation in effusivity reveals a sort of saturation at higher impact energy that can be also explained with the fact that the main contribution is done by the first shallow delamination. The jumpy behavior of curves in Figure 5 is probably related to the fact that the same impact energy may produce damage of different severity depending on sample thickness and hit point location.

The correlation coefficient between the functions $e_{rel}(W_{imp})$ and $a_{rel}(W_{imp})$ graphically presented in Figure 5 is 0.77 that is reasonably high to prove the fact that both effusivity and diffusivity can be linked to impact damage energy.

<table>
<thead>
<tr>
<th>Impact energy $W_{imp}$, J</th>
<th>Sample thickness, mm</th>
<th>$a_{rel} = \Delta a / a_{nd}$, %</th>
<th>$e_{rel} = \Delta e / e_{nd}$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0</td>
<td>1.8</td>
<td>11.9</td>
<td>49</td>
</tr>
<tr>
<td>10.0</td>
<td>1.7</td>
<td>2.2</td>
<td>64</td>
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<tr>
<td>62.4</td>
<td>4.7</td>
<td>49.7</td>
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</table>

Figure 5. Relative variations in effusivity and diffusivity vs. impact damage energy with (pulsed TNDT of eight CFRP samples by thickness of 1.6-4.8 mm)
2. Conclusions

The classical solutions for heat conduction in an adiabatic semi-infinite body and plate reveal two parameters which characterize temperature evolutions, namely, thermal effusivity in a one-sided test and thermal diffusivity in a two-sided test. Effusivity is determined in the temperature domain, therefore, this parameter is more susceptible to noise than diffusivity which is determined in the time domain. However, it has been found that the both parameters can be used for the characterization of subsurface defects, particularly, impact damage in composite materials. The preliminary experimental analysis performed on eight CFRP samples with the thickness of 1.6-4.8 mm which contained impact damage defects of the energy from 10 to 62 J has confirmed the presence of significant correlation between impact damage energy and the above-mentioned parameters, as well as between these parameters themselves.

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References