Non destructive testing for non cured composites: Air coupled Ultrasounds and Thermography

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Abstract
Novel materials and novel manufacturing processes are being involved in current aeronautical industry. This process has led the Non Destructive Methods to a continuous evolution state. One of the most innovative studies has been devoted to evaluate the inspection step during prepreg lay-up fabrication, with the objective that no parts with defects are inserted in the autoclave. Preliminary studies of the different Methods, and results obtained with Thermography and Air Coupled Ultrasound are described within this work. This study is completed comparing inspection on non-cured samples, and inspections of the same samples once they were cured.

Keywords: Non-Cured, Composite, Thermography, Air-coupled Ultrasound, Aeronautical, Algorithm

1. Introduction: Samples and Inspection Methods
Five different samples were specified for this study, four of them with different compaction processes and with different compaction grades, and the fifth one with six inclusions at different depths. Size of the inclusions: 10 mm x 10mm. Samples have 30 plies (7.5 mm) and 300 mm long and wide.

![Figure 1. Five non-cured samples were manufactured for NDT comparisons.](image)

The objective was to determine if different compaction levels and inclusions are detected in non-cured and cured samples.

In the initial approaches different inspection methods were considered in order to determine which method was the adequate to inspect non-cured samples where no contamination (no contact) was possible. These methods were applied for the inspection of non-cured samples, with different results. Initial material properties determination
was needed in order to define inspections. Final conclusion of these preliminary studies was that Thermography and Air-Coupled ultrasounds were the only two methods that could be used for inspection purposes ensuring no contamination to the material.

2. **Infrared Thermography**

Different cameras, excitation methods, inspection techniques and strategies were applied for non cured samples inspections. Evaluation of inspection results and post-processing tools have helped to obtain better results, and to define the final inspection parameters. Several algorithms have been considered also to facilitate the defect detection.

![Figure 2. Reflection Infrared Thermography.](image)

![Figure 3. Thermography results of a non-cured sample with inclusions.](image)

There are three thermographic NDT techniques currently in use for the detection and measurement of defects in composites, such as impact damage, voids, inclusions etc. The particular technique that should be employed for optimum results:

- Pulsed flash thermography (PT)
- Pulsed transient thermography (PT)
- Lock-in thermography (LT)

It will depend upon the sample material and thickness, and the test environment. The specific selection of camera type also varies widely, from cooled to uncooled, more or less resolution etc.
This research has been focused especially on Pulse Thermography, in which energy sources are used to pulse-heat the specimen surface. The specimen is heated from one side while thermal data are collected either from the same side (reflection mode) or from the opposite side (transmission mode). Defective zones will appear at higher or lower temperature with respect to non-defective zones on the surface, depending on the thermal properties of both material and the defect. The temperature evolution on the surface is then monitored in transitory regime using the IR camera obtaining thermogram sequences which can be later processed.

The principle of the Lockin thermography (LT) is based on creating a thermal wave on the surface of an object and analyze its penetration into the material. As the thermal wave penetrates into the object and it reaches a defect, it is partly reflected. The reflected part interferes with the wave entering at the surface, whereby an interference pattern in the local surface temperature and thus in the surface radiation are obtained.

### 2.1. Cameras
The features of the cameras used for this study are as follows:

<table>
<thead>
<tr>
<th></th>
<th>SC 640</th>
<th>SC 7500</th>
<th>CEDIP SILVER 450M</th>
<th>Vario CAM hr head</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature range</td>
<td>-40ºC – 1500ºC</td>
<td>-20ºC-3000ºC</td>
<td>-20 ºC - +900 ºC</td>
<td>-40 ºC - +600 ºC.</td>
</tr>
<tr>
<td>Integration time</td>
<td>3 µs -20 ms programmable (1 µs step)</td>
<td>10 µs a 20000 µs programmable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal sensitivity/ NEDT</td>
<td>&lt;30 mK @ +30ºC</td>
<td>&lt;25 mK @30ºC</td>
<td>&lt;0,025 ºC</td>
<td>&lt;30 mK @ +30ºC</td>
</tr>
<tr>
<td>Type of detector</td>
<td>Uncooled microbolometer</td>
<td>InSb Cooled 640 x 480 pixel</td>
<td>InSb (Stirling cooled) 320x256 pixele</td>
<td>microbolometer 640x480 pixel</td>
</tr>
<tr>
<td>Spectral range</td>
<td>7.5-13 µm</td>
<td>1.5-5.1 µm</td>
<td>3,6-5 µm</td>
<td>7.5 -14 µm</td>
</tr>
<tr>
<td>Frame rate</td>
<td>30 Hz</td>
<td>1-380 Hz Full Frame rate</td>
<td>up to 383 Hz full-frame (20 KHz subwindowing)</td>
<td>50-60Hz</td>
</tr>
</tbody>
</table>

### 2.2. Infrared Thermography for non cured samples: Cameras SC 640 & SC 7500
In this paper, different approaches have been used for the inspection of cured and non-cured samples.

#### 2.2.1 Pulsed Thermography
Figure 4 shows the setup used in most of the tests, although some changes have been made depending on the experimental approach.
The main target was to obtain the adequate strategy to detect hidden defects: camera, excitation method, etc.

The temperature difference was induced in all the samples with a 1500W halogen lamp in reflection mode using different heating pulses. However, no valid results showing these compaction differences were obtained.

Firstly, measurements in non-cured samples were performed using two IR cameras SC 640 and SC 7000 and two active methods: pulsed thermography using flash lamps and transient thermography using halogen lamp.

Initial tests were carried out during prepreg lay-up manufacturing. Defects were inserted in layers 2, 15 and 28 (samples with 30 layers and 7.5 mm thickness). The samples were inspected after every layer, in order to determine which was the maximum number of layers over the defects allowed for defect detection. The external thermal stimulation of the inspected sample surface was performed by a 1500W halogen lamp at a distance of less than one meter and varying pulse duration from \( t_1 \) to \( t_3 \). The temperature evolution of the surface sample was recorded by the IR camera.

Once the results have been analyzed, it is concluded that defects have been detected with a maximum of 6 layers over them. In Figure 5 we can see the defects inserted in layer 2 can be detected in layers 3 (one lay over defect), 4 (2 lays over defects) and later in layer 8 (not detected in layer 6). It is interesting to note that a compacting process
was performed on layer 8, being therefore the possible reason that enables the detection. The non-uniform heating of the surface become an important uncertainty source in active thermography. Since the defect detection is based on temperature differences, the non-uniform heating can lead therefore to misunderstandings.

In applying thermal imaging to the non-cured sample once finished (30 layers), the only modification to the system described before was to replace the halogen heating with flash heating and the SC640 with the SC7000.

Since the sample was already manufactured, the whole depth (30 layers) was inspected. Thus, the following setups were used: a) SC 640 + Flash, b) SC 7000 + Flash, c) SC 7000 + Halogen Lamp.

![Thermograms obtained in the non-cured sample with different configurations](image)

Figure 6. Thermograms obtained in the non-cured sample with different configurations

Proceeding as the previous inspections, no significant differences have been obtained: Only the most superficial defects could be detected. When flash heating was used, defects appeared with worse resolution. Higher frequencies than 100 Hz don’t provide better results in depth detection neither in resolution.

Considering the particular defectology present in these specimens, the results are analyzed in a comparative way by subtracting the results and studying the contrast. The inclusions were detected, see Figure 7.

![Result of the front face thermographic inspection to the cured sample with inclusions](image)

Figure 7 Result of the front face thermographic inspection to the cured sample with inclusions.
Regarding the different levels of compaction, in Figure 8 several images taken from different specimens under the same test conditions and data processing are shown. Under the same test and analysis conditions the results can be considered comparable.

![Figure 8 Results of the thermographic inspections to different samples with low level of compaction.](image)

Taking the results into consideration, and the comparative analysis between them, it is not possible to confirm the existence of a lack of compaction. Different patterns of contrast are detected in the thermal images, which are probably due to differences in the manufacturing process of each of the specimens. However, this pattern does not verify the presence of defects.

### 2.3. **Infrared Thermography for cured samples: Cameras SC 640 & SC 7500**

#### 2.3.1. **Pulsed Thermography**

Once the non-cured samples have been inspected, measurements in the cured sample have been performed in order to compare the results before and after autoclave. The setup of Figure 4 has been used, in reflection mode but also in transmission.

![Figure 9. Thermograms obtained using a setup of Figure 4 in both modes with different heating pulses.](image)

Thermograms from Figure 9 shows that only the most superficial defects are detected in reflection mode. In transmission mode, no defect can be detected regardless of the duration of the applied heating pulse.

#### 2.3.2. **Lockin Thermography**

Set up showed in Figure 10 was used for Lockin Thermography:
The tests were performed by means of the SC 7000, along with the associated SW and using Power Electronics module 22kW including two excitation sources (2.5kW each).

The results of the inspection carried out with Lockin and PPT strategies will be shown as follows.

Data obtained by optical stimulation, in either PT or LT, is processed by the Fast Fourier Transformation (FFT) leading to the PPT. In this mode the FFT of the original digital thermal signal is performed to analyze the experimental temporal data series in a frequency domain. Thus, computed phase diagrams are obtained which are particularly interesting because are practically not affected by heating problems such as reflections with the surroundings, emissivity variations, non-uniform excitations, etc. For this reason, the images analyzed from now on will be phase images.

![Figure 10. Set up used in cured sample](image)

From the analysis of the phase images obtained (Figure 11) it is observed that detection of all the defects at different depths is obtained with transmission mode and PPT. Thus, heating during t8 in a distance of 20 cm from the surface of the sample and acquiring images at the same distance from the surface, almost every defect can be clearly seen. In this case, the heating pulse is much longer than the one used in the reflection mode due
to the sample thickness. With the Locking phase image evaluation, despite performing several inspections, defects at higher depths have not been detected. Only the superficial ones are visible.

2.4. **Infrared Thermography for cured samples: Camera CEDIP SILVER 450M model.**

The thermal camera used in the development of this project is the CEDIP SILVER 450M model. Features of this camera are described in Cameras Chapter.

Different excitation techniques (optical stimulations) have been used for the inspections. The optical stimulation equipment used in thermographic inspections consist on the one hand of several flash lamps of 6 KJ each one, with their corresponding accumulators, and on the other hand, of several halogen lamps that are modulated through the test control software.

It should be mentioned that the temperature of the tested specimens was kept at all times below 60 °C to prevent from overheating and damage to the specimens.

2.4.1. **Pulsed Thermography**

Flash lamps are employed in this case to introduce the necessary energy to the sample. (2 lamps, recording period: t7) This technique consists of recording the cooling down process of the surface to be studied after applying a pulse of light of a very short duration.

2.4.2. **Lockin Thermography**

This technique involves the modulation in amplitude of the emitted radiation, which heats the surface of the specimen to be studied. Data is acquired during the stimulation and is simultaneously processed by a Lockin algorithm. Therefore, when the test finishes, amplitude and phase results of the test are directly obtained.

<table>
<thead>
<tr>
<th>Nº of lamps</th>
<th>Amplitude (% energy)</th>
<th>Frequency (Hz)</th>
<th>Nº of acquisition periods</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>80</td>
<td>0.5</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>0.1</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>0.05</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>0.01</td>
<td>2</td>
</tr>
</tbody>
</table>

2.4.3. **Step Heating Thermography**

This technique involves applying heat steadily over a period of time. In this type of test both the heating period and the cooling period are recorded, and subsequently analyzed. This test was also performed in both transmission and reflection configurations.
Table 2 Parameters employed in the Step Heating tests.

<table>
<thead>
<tr>
<th>Nº of lamps</th>
<th>Amplitude (% energy)</th>
<th>Stimulation period (s)</th>
<th>Total recording period (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>80</td>
<td>10</td>
<td>20</td>
</tr>
</tbody>
</table>

2.4.4. **Data Processing Techniques**

In the following paragraphs it can be found a description of the data processing techniques applied to the conducted tests.

**A) Principle component analysis (PCA)** is a statistical technique for synthesis of information. Its objectives are, first, to reduce the number of variables in a data set to a smaller number, losing as little information as possible, and secondly to highlight differences and similarities between data.

Despite initially being a technique to reduce the volume of information, has been demonstrated good results in its application to thermographic data. Because the property to preserve the most relevant information allows to eliminate noise and facilitate the detection of defects.

These main components are obtained from the singular value decomposition (SVD) of the temporary thermal data matrices. Before applying the decomposition, the 3D array representing the thermographic sequence must be transformed into a new 2D matrix whose SVD is given by the next expression:

\[ A = U \cdot S \cdot V^t \]

Where \( A \) is the input matrix, the columns of \( U \) are the empirical orthogonal functions, and \( S \) is the diagonal matrix of the singular values of \( A \).

For the calculation of the third and fourth order moments of the temporal evolution of each pixel, it was implemented a series of functions that operated sequentially allow to obtain the result in a final image, which is the graphical representation of the value of the corresponding statistical moment.

**B) The skewness** is the third standardized moment of a distribution. The term “moment” is used to represent the expected values of different powers of a random variable. It is used to determine the degree of fit of data in regards of a particular type of distribution.

The expression for calculating the skewness or third order moment is as follows,

\[ k_3 = \frac{E[(x - \mu)^3]}{\sigma^3} \]

Where \( \mu \) is the mean value, \( \sigma \) is the standard deviation and \( x \) the input data.

**C) The kurtosis** is the fourth standardized moment of a distribution. It is generally defined as a measure that reflects the degree to which a distribution is peak shaped.
In particular, the kurtosis provides information about the height of the distribution in relation to the standard deviation value. The formula for the calculation of the kurtosis or fourth order moment is as follows,

\[ k_4 = \frac{E[(x - \mu)^4]}{\sigma^4} \]

Where \( \mu \) is the mean value, \( \sigma \) is the standard deviation and \( x \) the input data.

**D) Polynomial fit and derivatives:** It has finally developed this method, based on the TSR technique (Thermal Signal Reconstruction). This is a filtering method which sensibly improves the results of the thermographic inspections by adjusting the temperature time history of each pixel to a degree polynomial, as shown in the following equation,

\[ T(t) = a_n t^n + a_{n-1} t^{n-1} + \cdots + a_1 t + a_0 \]

Being \( a_n, a_{n-1}, \ldots, a_1, a_0 \) the coefficients of the polynomial fitting. The obtained polynomial is derived successively for the first and second derivatives. Differentiation of these polynomials produces an increased signal to noise ratio (SNR), thereby reducing the level of noise.

### 3. Air Coupled Ultrasounds

**3.1. Inspection strategy.**

A detailed experimental study of the properties of the uncured laminated prepregs was performed in order to determine velocity and attenuation of ultrasonic waves in this non-cured material. Then inspection strategy was defined in order to perform the ultrasonic acquisition data while the sample was manufactured. Air-coupled ultrasound probes, mechanical device, electronics, material and inspection scheme were specifically defined in order to ensure final results.
Ultrasonic properties of un-cured prepreg plates where initially measured employing the technique described in [5], in the frequency range 0.5-1.0 MHz. This revealed that the prepregs exhibit a relatively low ultrasonic velocity (about 1300 m/s) and a extremely high attenuation coefficient: 600 Np/m at 0.6 MHz that increases rapidly with the frequency [6]. This huge attenuation coefficient makes extremely difficult to inspect these materials at frequencies over 1 MHz. Therefore a low frequency was selected (0.25 MHz) to mitigate the influence of the attenuation. However, even in spite of the selection of this low frequency the challenge faced by the air-coupled ultrasonic technique is very demanding as it involves the transmission through the sample and the metallic mold where it is manufactured. Therefore, highly sensitive air-coupled (peak sensitivity at -25 dB) and wide band transducers were designed and manufactured according to [7]-[9]. Wide band is important because it eases the isolation of the through transmitted signal from other reverberations produced in the transducers/sample cavities. Time and frequency response of the pair of transducer in through transmission mode is shown in Figure 14 and Figure 15.
Figure 15. Frequency response.

Transmitter-receiver response. Separation 20 mm, excitation semicycle of square wave (200 V amplitude), no amplification in reception. Received signal digitized by a Tektronix DPO 7054 Oscilloscope. Frequency response is given by the sensitivity (SNS), defined as: SNS = 20 log (abs(FFT(Vrec)/FFT(Vapp))), where Vapp is the effective voltage applied to the terminals of the transmitter transducer and Vrec is the voltage measured at the terminals of the receiver transducer.

4. Results and discussion

Five samples were considered for this study. Four of them with different grade of compaction, and a fifth one with inclusions.

Different inspection strategies with Thermography and Air-coupled Ultrasounds were carried out in order to determine those levels of compaction, but not relevant results were obtained.

Concerning Thermography the following conclusions were obtained:

- Using a LWIR camera along with halogen lamp in reflection mode, superficial defects (up to 6 layers) can be detected, whether cured or non-cured samples are inspected.
- Better results were obtained with halogen lamp excitation.
- Several sampling frequencies were evaluated, obtaining as a conclusion that better results in depth detection and in the resolution are obtained with frequencies lower than 100 Hz.
- Post Processing of raw data is giving significant help for data evaluation.

After completing all the inspections with non-cured and cured-samples, and with Thermography and Air-coupled Ultrasounds, it is concluded that non-cured samples can be inspected with both Inspection Strategies with no material contamination, and detecting inclusions in the near surface, up to 6 layers for Thermography and 4 layers for Air-coupled ultrasounds.
References


[4]. C. Ibarra- Castanedo. “Quantitative subsurface defect evaluation by Pulsed Phase Thermography: Depth retrieval with the phase”, 2005


[12]. "A quantitative comparison of stimulation and post-processing thermographic inspection methods applied to aeronautical carbon fiber reinforced polymer” – Book of proceedings of QIRT 2012