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Delamination Detection By Thermography

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Abstract

Infrared thermography is a two-dimensional, non-contact technique allowing surface temperature mapping by providing colourful images easy to interpret through the use of an external energy source and an infrared detector. The attention of the present study was focused on the aid provided by active thermography for non-destructive evaluation of composite material. In present work the experimental analysis was performed by testing several specimens, which were made of E glass woven with epoxy which included the most commonly encountered kinds of damage called delamination artificially created in composite laminate specimens. From the experimental investigations, the effects of delamination area on the detection were elucidated. Also the applicability of the present thermograph method depends on a relative difference of thermal property between the delamination and its surrounding was explained.

Keywords: Active infrared thermography, Composite material, Delamination.

1. Introduction

Non-destructive inspection methods must be reliable, efficient, non expensive, fast and easy to use. Moreover, as materials and processes are constantly changing, inspection techniques should adapt to this evolution, too. Among various non destructive inspection techniques currently used is infrared thermography which a non-contact inspection tool. It is relevant whenever there is a thermal contrast between the inspected object and the surrounding area of interest [1-3].

Thermography is a technique of producing a live thermal picture of an object based on the infrared radiation received from it (emitted by any object). In pulse thermography, a thermal pulse is applied to the material to be inspected. Following the application of this thermal pulse, a measurement of the temporal evolution of the specimen surface temperature is performed with an infrared camera allowing subsurface defects to be revealed. The temperature of the material changes rapidly after the initial thermal perturbation because the thermal front propagates, by diffusion, under the surface and also because of radiation and convection losses. The presence of a defect reduces the diffusion rate so that when observing the surface temperature, defects appear as areas of different temperatures with respect to surrounding sound areas once the thermal front has reached them. Consequently, deeper defects will be observed later and with a reduced contrast [4].

Thermography is now a popular non destructive testing method for detecting defects in composite structures. Active thermography method for composites is well reported in literature [5-6]. An active thermography system consists of a heater unit for controlled heating of the test specimen, an infrared camera for capturing the surface temperature evolution of the specimen, and a data acquisition system for acquiring the corresponding infrared images over a specific period of time.

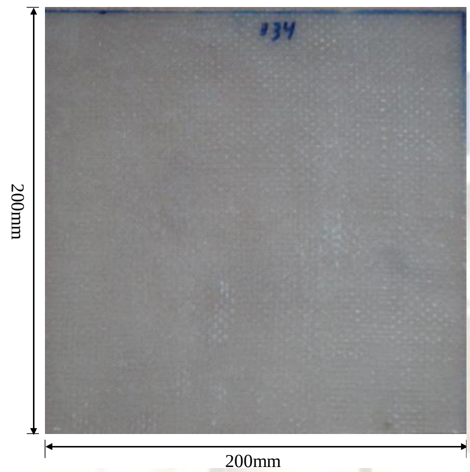
Delamination is one of the most common defects for composite materials. It leads to the degradation of mechanical properties and also causes the failure of the overall composite component. To detect delaminations and ensure the safe operation of composite components, non destructive evaluation techniques are used. An extremely promising technique is thermography, which has the advantage of good fault detection possibility along with the capacity to inspect a large area within a short time. Thermography is also applicable to a wide range of materials, including glass fibre, carbon fibre composites and metallic materials, where specific excitation techniques are needed for each application. To inspect defects over a large scale and at large stand-off distances, integration of thermography has been investigated [7].

The present paper describes experiments conducted with the active thermographic procedure, which consists in sending a controlled heat flux using an external heat source (hot air blower) to the inspected composite laminate plate. The objective of this paper is to present results from some experiments using active thermographic inspection procedure on composite material consist of E glass woven and matrix with deliberately inserted artificial delamination. Effect of delamination area and variation of thermal properties between delamination and basic material were studied by analyzing the surface temperature profiles and thermal contrasts obtained from experimental active thermal imaging system.

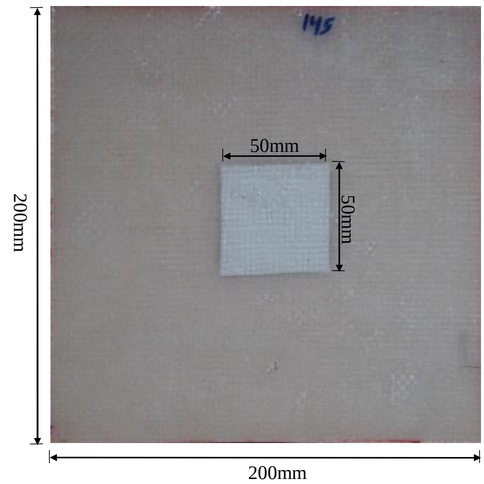
2. Experiment 1

2.1 Samples preparation

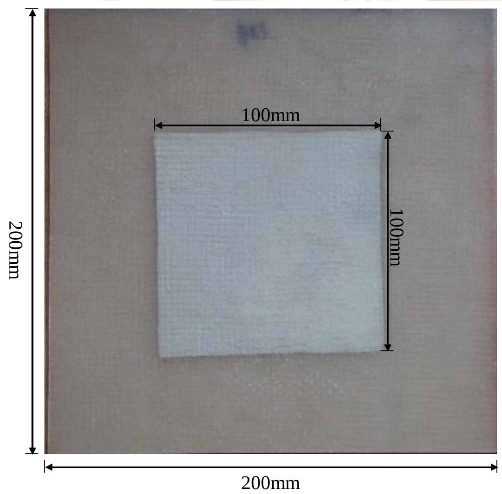
Cross ply 8-layered plates include E glass fibres embedded in an epoxy matrix were used in present experimental work, with an overall laminate thickness of 2.5 mm. The dimensions of square specimens were (200x200) mm^2. Aluminum foils as the man-made delaminations were manufactured with different areas (50x50, 100x100, 150x150) mm^2 inserted in the central mid plane of some plates as shown in Figure.1.



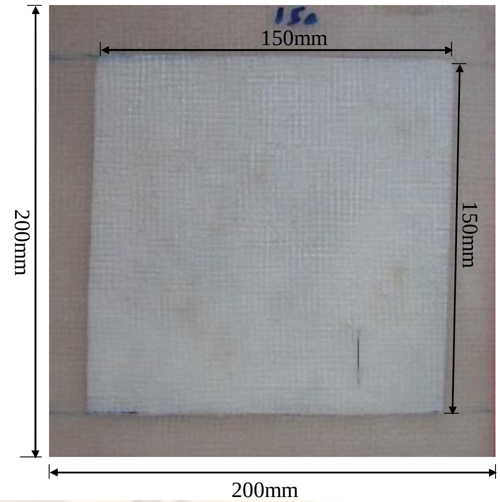
a) Healthy plate (no delamination)



b) Delamination area (50x50) mm^2



c) Delamination area (100x100) mm^2



d) Delamination area (150x150) mm^2

Figure.1 Test specimens

2.2 Active thermography experimental set-up

The investigation of composite materials most often demands the active method. The active approach requires an external heat source to stimulate tested materials. The present experimentation was carried out by using a hot air blower to heat the sample with 2.5 kW output power uniformly. The heat source was kept 30 cm from the investigated plate and the camera was held 70 cm from the sample. The experimental setup for active infrared thermography is shown in Figure.2. The infrared camera measures the thermal transient at the surface of the plates resulting from the heating of the plates. The infrared camera captures the thermal information and generates two dimensional thermogram which was saved in the camera memory and then transferred to the computer for further processing. The emissivity was set at 1 (black body), a value which offered the image with the best contrast with the background.

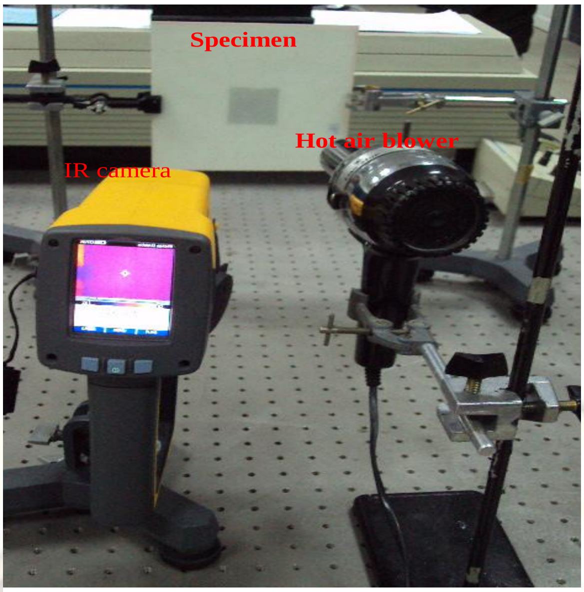
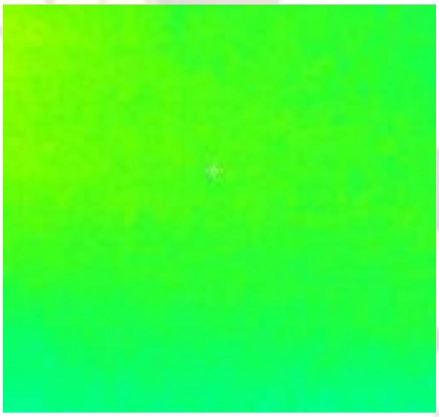


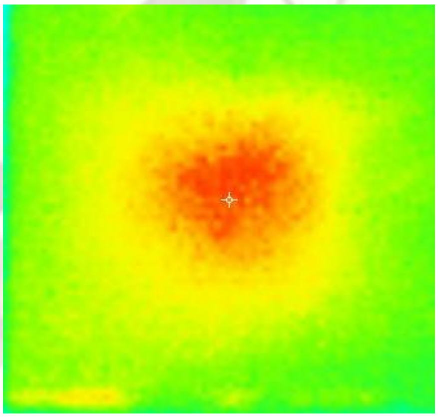
Figure.2 Active thermography experimental set-up

2.3 Results and discussion

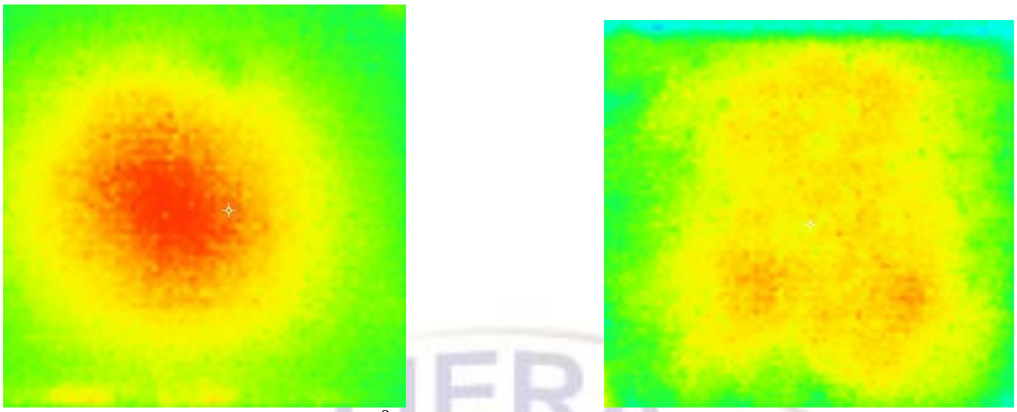
The surface temperature distribution images over the laminated composite plates were obtained after the end of heating time 7 seconds using experimental set-up. All thermograms highlight the delaminations in the composite plates according to their areas but with various accuracy. Some of them are being influenced by non-uniform heating, because the heating time is short. In the thermograms associated to these delaminated plates, one can observe, besides the central induced delamination, an extension of deterioration during the manufacturing process. Thermal contrast was obtained from the fact that, the Aluminum foil at the place of delaminations behaves like a barrier which makes surface temperature above the delaminated surface slightly warmer than the round healthy region. Present thermal contrast value was measured by thermography to detect delaminations which were used to analyze for varying areas. The surface temperature distributions obtained from active thermography experiment are shown in Figure.3.



a) Healthy plate



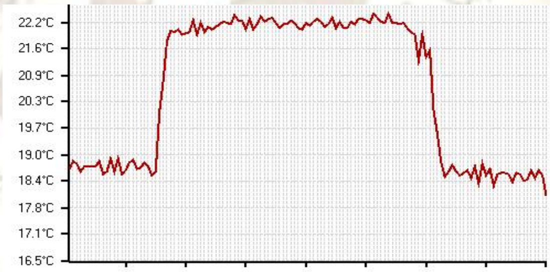
b) Delamination area (50x50) mm^2



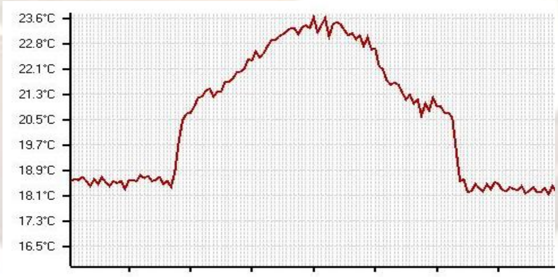
c) Delamination area (100x100) mm^2 d) Delamination area (150x150) mm^2

Figure.3 Surface temperature distributions for healthy and delaminated plates

The temperature profiles across the centre lines of the healthy and delaminated plates are shown in Figure.4.

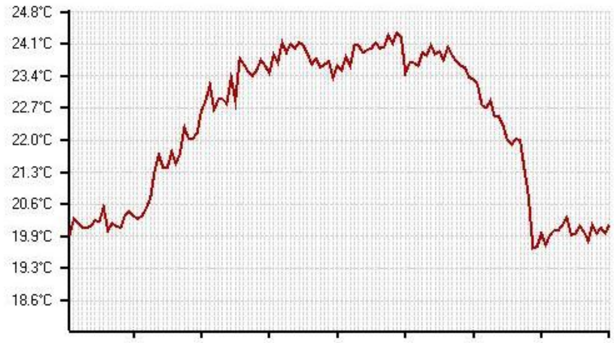


a) Healthy plate



b) Delamination area (50x50) mm^2

c) Delamination area (100x100) mm^2



d) Delamination area (150x150) mm^2

Figure.4 Surface temperature profiles across the centre line of the plate

Figure.3 (a) and Figure.4 (a) show that the temperature was almost uniform throughout the surface of healthy plate. From the Figure.4 (a) the average temperature across the length of the healthy plate is 22.4°C experimentally. Figures.3 (b, c, d) and Figures.4 (b, c, d) show that there are some non-uniform temperature distributions at the specific location of simulated delaminations, revealing that the plate does have delamination. The approximately maximum thermal contrasts obtained experimentally at the delamination locations were 5.1°C and 5.7°C for delamination areas (50x50 and 100x100) mm^2 respectively. When the area of the delamination increases, the thermal contrast was also increased except for largest delamination area (150x150) mm^2 the maximum contrast decrease to 3.85°C because of the short time of heating, also in the case of the largest delamination, there was more air trapped between the inserted foil and the resin promoting the dissipation of heat in this delaminated area, but when the time of pre heating increased to 10 seconds instead of 7 seconds, the contrast increases to 6.1°C as shown in Figure.5. However the localized contrast regions are clearly identified even for small delamination area.

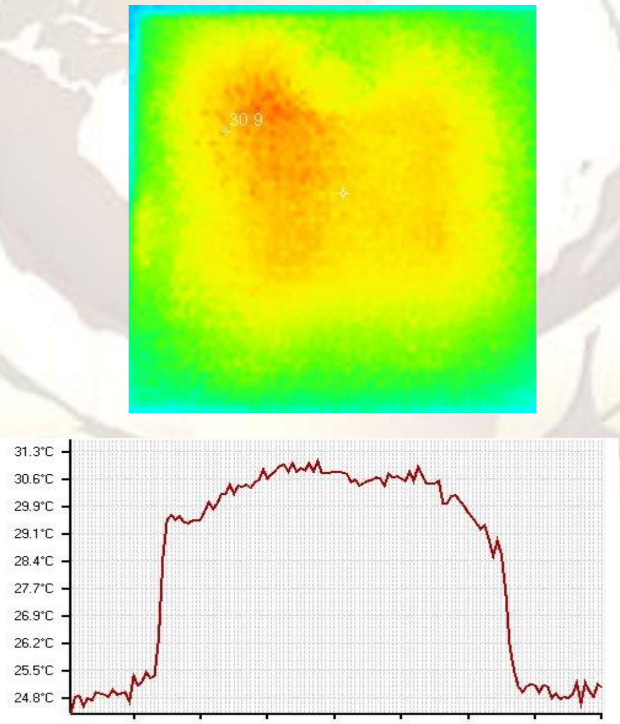


Figure.5 Surface temperature profile across the centre line of plate with delamination area (150x150) mm^2 after heating 10 seconds

It was observed that after the end of the pre-heating process, temperature profiles revealed the internal delamination. Because of different thermal conductivity between delamination and healthy area existence the defect was manifested by higher temperature in the delaminated region. It is possible to vary heat input and heating time to obtain best delamination detectability, which depends on the material being tested, its thickness, depth and area of the delamination. In order to get a clear picture of searched delaminations the pre-heating time cannot be too long. Long-time pre-heating led to even temperature distribution over entire searched surface. This effect was observed independently on type of a heat source (flash or heater radiator) and on the position of the heat source. After many trials it was stated that an appropriate warm-up time in present case of composite laminate materials should be about 7 seconds. It is also worth mentioning that although the best possible results concerning the clearest images (high thermal contrast) were acquired at relatively short periods during the cooling down process (composites have relatively low thermal conductivity values). There are of course other limitations, mostly concerned with the size of the delamination, the resolution of the infrared camera, the timing image capturing during the transient phase and the thermal properties of the examined material. These limitations should be account for the significant accuracy to estimate the delamination shape in laminated composite structure. Generally all objects radiate energy continuously in the form of electromagnetic waves mainly in infrared region produced by thermal vibrations of the molecules. The relationship governing radiation power from hot objects according to the Stefan-Boltzmann law is:

$$P = \varepsilon \, \sigma \, A T^4 \qquad (1)$$

Where,

P = Radiated power (watts)

A = Radiating area (m^2)

σ = Stefan-Boltzmann constant (5.6703×10^{-8} W/m^2K^4)

ε = Emissivity (=0.03for Aluminum foil)

T=Temperature of radiator (in Kelvin)

The total radiated power from delaminated specimens can be calculated according to Eq1, that showing below in Table 1

Table 1 Total radiation power from delaminated samples

Delamination area (mm^2)	Total radiation power (w)
50x50	0.0322
100x100	0.129
150x150	0.290

The relation between total radiation power and the delamination areas shown in Figure.6.

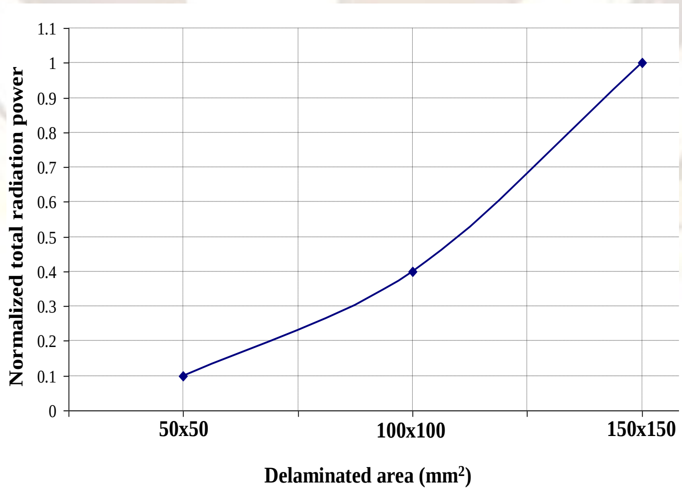
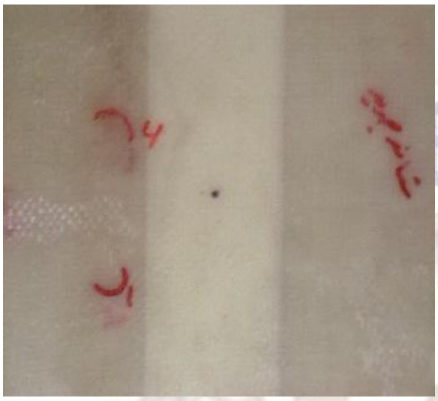


Figure.6 Variation of total radiation power with delaminated areas

3. Experiment 2

3.1 Specimens preparation

E glass woven with epoxy specimens were fabricated including artificial delaminations located at same depth 1.25 mm Figure.7.The areas of these test samples were (205x205) mm^2, number of layers was 8 and the area of delamination was (60x205) mm^2.The simulated test plates used in present experiment consist of different delamination thermal properties, such as sample 1 contains simulated delamination Aluminum foil coated with special isolated wax and sample 2 with simulated delamination air gap. All these simulated delaminations have different thermal properties.



a) Sample 1 (Aluminum delamination)

b) Sample 2 (Air gap delamination)

Figure.7 Test specimens

3.2 Delaminations description

A brief description of different anomalies in the previous test specimens is provided below:

1. Air gap delamination, a manufacturing defect where air was trapped between layers of fiber glass so that there was glass fiber but no resin to bond it.
2. Aluminum alloy delamination, an area of specimen whereby one layer of fiber glass has separated from the adjacent layer, by using an Aluminum foil coated with special wax.

3.3 Experimental set-up

The schematic of the experimental setup is shown in Figure.8. A heat blower was used as a heat source to all samples. The distance between the heating element and the test plate for each experiment was kept constant. A gap of approximately 30 cm was maintained between the heat source and the test sample.

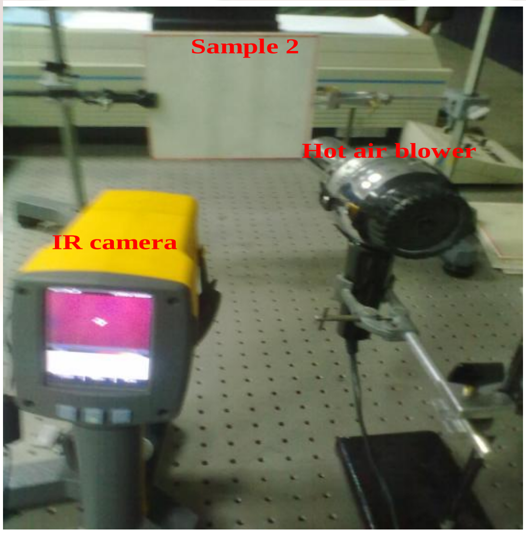


Figure.8 Active thermography experimental set-up

3.4 Results and discussion

All samples considered in present experiment were heated for different time periods, i.e. 3 seconds, 7 seconds, 12 seconds, and 1 min. A thermal camera was used to record the thermal intensity decay data with cooling time, following the removal of the heat source. When the test samples were heated for 3 seconds, no significant temperature rise was observed whereas, when heated for 1 minute, the thermal camera produces saturated images. Hence, for the cases considered in the present experiment it was observed that the optimal heating times for delamination detection of different thermal properties were 7 and 12 seconds. Generally in present case, relation between temperature and time elapsing after pre-heating interruption achieved in delamination area, were characterized by a higher temperature in connection to the rest of the specimen, also the cooling process in the area with delamination runs much longer. Figure.9, gives a direct impression of the behaviour of the temperature at the surface of the test samples, after the maximum value of the temperature was reached. The Figure shows the temperature decay of different simulated delamination samples after heating each one uniformly and separately for 7 seconds. However, it was observed that, temperature decays in sample 1 and sample 2 cases have similar decreasing trends over the cooling cycle and were difficult to distinguish when heated for 7 seconds.

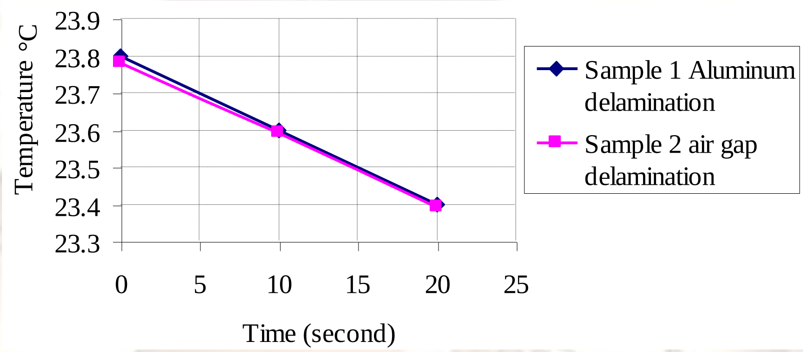


Figure.9 Temperature decay for different delamination thermal properties heated for 7 seconds

The thermal images show prominent thermal decay when heated for 12 seconds, compared to the case of heating for 7 seconds, the corresponding temperature decay is shown in Figure.10. Sample 1 attains maximum temperature when heated for 12 seconds followed by sample 2.

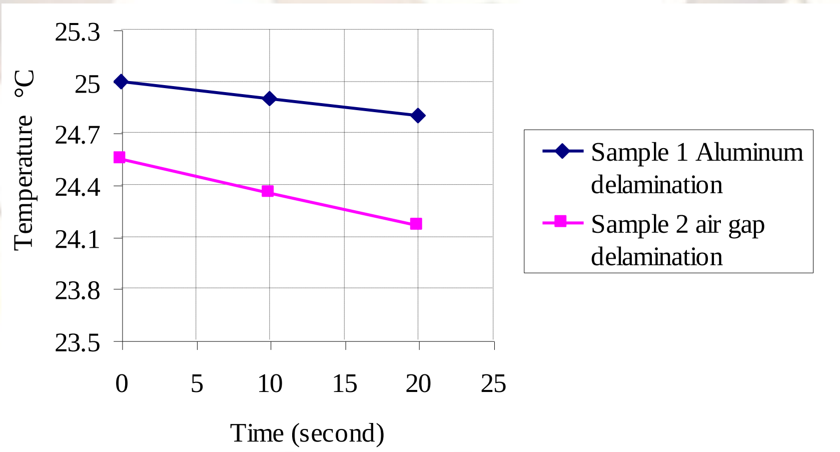
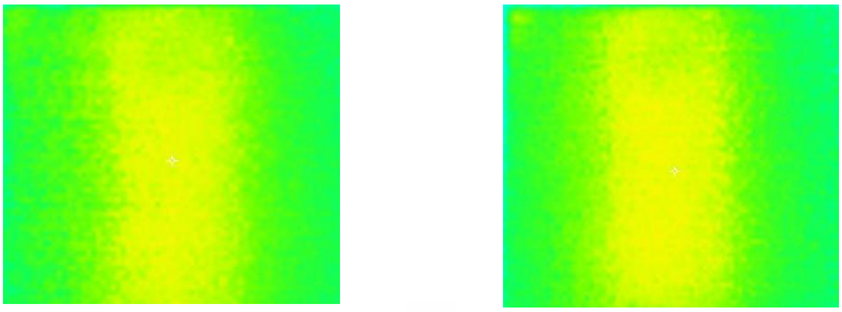


Figure.10 Temperature decay for different delamination thermal properties heated for 12 seconds

Thermal camera images for sample 1 and sample 2 are shown in Figure.11 and Figure.12. In the following thermograms associated to delaminated samples, one can observe, besides the central artificial delamination, a little deterioration at upper portion of the artificial delaminations during the manufacturing process.



a) Sample 1 (Aluminum delamination) b) Sample 2 (Air gap delamination)

Figure.11 Thermal camera images after 7 seconds of heating

a) Sample 1 (Aluminum delamination) b) Sample 2 (Air gap delamination)

Figure.12 Thermal camera images after 12 seconds of heating

As heating time increases, the contrast between delamination and healthy area increases and delamination of both samples show different contrast depending on its thermal properties as shown before in Figure 11 and Figure 12. The heating time of 12 seconds instead of 7 seconds leads to increase of the heating energy, because the heating energy must be enough to creat thermal contrast between healthy and delaminated area, which can be sensed by infrared camera. If the energy is not enough as introduced before at heating time 7 seconds, the delamination may be difficult to extinguish, especially when the comparing of delamination appearance was according to the type of delamination thermal properties. Therefore the delamination visibility depends strongly on the thermal properties of both the basic material and the delamination itself. It is demonstrated that the heating temperature plays an important role in the detection of delamination which increase amount of thermal radiation that the camera received from surface, also by increasing heating time, minimized the effects of non-uniform temperature distribution, one of the main problem that affect the quality of this type of non destructive test. The suitability of infrared thermography to non destructive testing depends on the ability to detection of the temperature variation or thermal contrast induced by a delamination which greatly effected by thermal properties of delamination and basic material. The present experiment confirmed that thermal properties of a delamination material can be concluded from sequential recording of thermograms including temperature distribution on the surface of the plate under test starting at the beginning of the cool down phase. Thermal images allowed determination of whether specific material of delamination was of higher or lower thermal properties than the healthy material.

4. Conclusions

In this work, the study of delaminations in composite laminate plates using thermography technique was done experimentally. The experiments were intended to detect delamination of variable areas and thermal properties existing in composite laminate plates. The following conclusions can be drawn:

1. Thermographic images analysis is an effective method for revealing delamination in the composite materials.
2. Thermography methods require specific skills to achieve good results in delamination detection for composite material.
3. Because of different thermal conductivity between delamination and healthy area existence the defect was manifested by higher temperature in the delaminated region.
4. It is possible to vary heat input and heating time to obtain best defect detectability, which depends

on the material being tested, its thickness, depth, area of the delamination, the timing image capturing during the transient phase and the resolution of thermal camera.

5. The heating temperature plays an important role in the detection of delamination which increase amount of thermal radiation that the camera received from surface.

6. The delamination visibility depends strongly on the thermal properties of both the basic material and the delamination itself.

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