International Journal of Mechanical Engineering and Robotics Research

ISSN 2278 – 0149 www.ijmerr.com
Vol. 1, No. 3, October 2012

Research Paper

ACTIVE INFRARED THERMOGRAPHY TECHNIQUE FOR THE NON DESTRUCTIVE TESTING OF COMPOSITE MATERIAL

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Delamination is one of the most common defects in laminate composite materials. To detect delaminations, different non-destructive test methods such as infrared thermography methods are currently widespread for non-destructive inspection, recommended for evaluating composite materials mostly in the active variant. The principle behind infrared thermography consists in highlighting the relevant differences of temperature, by comparing the temperature of the area without defect to the defected area temperature. Active infrared thermography refers to the group of methods employed to inspect the integrity of materials or systems through the use of an external energy source and an infrared detector. The paper presents several experimental examples concerning the use of active thermography in the non destructive evaluations of composite materials. The paper presents the analysis of results obtained by active infrared thermographic testing of E glass woven (0, 90) reinforced polymer plates of eight plies containing artificial delaminations. For this study, number of composite plates were manufactured with different known depths of delamination implanted using Aluminium foil coated with special wax and different thickness of delamination embedded at same depth. The aim of the present paper to investigate experimentally the ability of active thermography to detect the delamination based on its depth location and thickness. Thermal images obtained by experiments using infrared camera were used to extract surface temperature profiles above the delaminated and non-delaminated surfaces on the specimens. The dependency of thermal contrast on delamination depth and delamination thickness was also investigated.

Keywords: Delamination, Active infrared thermography, Thermal contrast, Composite material

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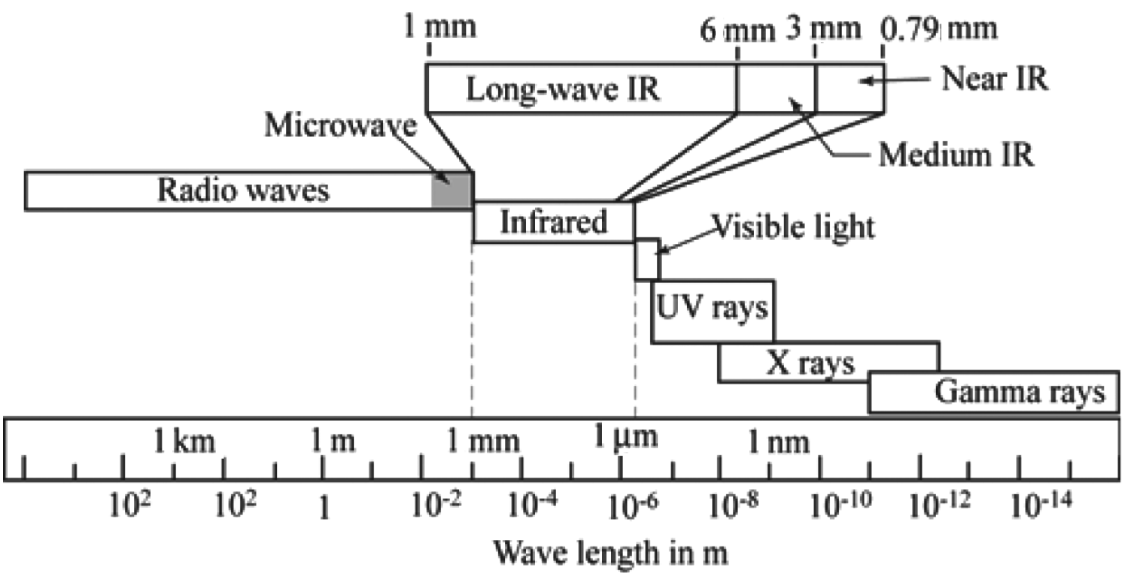
INTRODUCTION

Due to inherent complexities of composite structure manufacturing, various types of defects such as voids, inclusions, improper cure, delamination, disbond, etc., may crop into the final product made of composite material (Ray *et al.*, 2007). The proper assessment of such defects is essential for utilization of full potential of these materials. Various non destructive testing methods are available to inspect the composite structures. These include x-ray radiography, ultrasonic testing, time of flight diffraction technique, and thermal imaging. Thermography imaging technique has been widely used over the decades to evaluate the integrity of materials, joints, electrical connections in a wide range of industrial as well as research fields (Maldague, 1992). Active infrared thermal provides fast, safe, non-contact and non destructive tool for evaluation of sub-surface defects in materials. Typical applications in the material evaluation field include the investigation of composite materials, ceramics, bonded structures, metals, and coated surfaces. The thermography method can be used as an alternative or complement to conventional non destructive testing techniques (Terumi *et al.*, 1999; and Maldague, 2001). This examination technology does not affect the material or structure's future usefulness and at the same time providing an excellent balance between quality control and cost-effectiveness (Paritosh *et al.*, 2006). In active method of thermal non destructive testing, the object is excited by a heat source and the transient temperature behaviour on the surface of the object is monitored by using thermal imaging equipment called infrared camera. The influence of the thermal wave that diffuses into the material on the surface of the specimen was observed and these observations were used to detect and characterize the surface and subsurface delamination (Biju *et al.*, 2009). The presence of sub-surface anomalies in the object interfaces with the perturbation of heat flow and causes temperature contrast at the surface. Thermal non destructive testing has been previously well reported for various applications such as detection of delaminations in composite materials, (Wong *et al.*, 1999; Maldague, 2001; Omar *et al.*, 2006; Mabrouki *et al.*, 2009; Genest *et al.*, 2009; and Vageswar *et al.*, 2009). Vijayaraghavan *et al.* (2010) reported several experimental works on the pulsed thermography of carbon fibre reinforced polymer for the investigation of interfacial defects. Mitsui *et al.* (2000) conducted experimental study for detection and thickness evaluation of delamination between the fibers reinforce plastic sheet and concrete by infrared thermography. Mirela *et al.* (2007) demonstrated the possibility of identifying the defect type in complex structure carbon fiber reinforced plastic samples inspected by thermography using experimental and Finite element method results. Mayr *et al.* (2008) presented comprehensive analysis of geometry and excitation effects of pulsed thermography on curved carbon fiber reinforced plastic components containing delaminations. Mabrouki *et al.* (2009) applied active thermography for the detection of delaminations in E-glass fibre. This paper aims to analyse experimentally the ability of active thermography test to detect the delaminations according to their depths and thickness in composite laminate plates and the dependency of thermal contrast on delamination depth and delamination thickness was also investigated.

THERMAL NON DESTRUCTIVE TESTING

Thermal non destructive testing, also referred as Infrared thermography, is a non-destructive, non-intrusive, non-contact mapping of thermal patterns on the surface of objects. Generally, It is used to diagnose thermal behaviour and, thereby, to assess the performance and the integrity of material, products and processes. All surfaces of the objects warmer than absolute zero emit electromagnetic radiation energy in the infrared region of electromagnetic spectrum which, lies between visible light and radio waves. The electromagnetic spectrum illustrated in Figure 1 shows the region of X-rays, radio waves, light waves (ultraviolet and visible) and infrared radiation. Infrared region of the spectrum extends between 0.79 μm and 1 mm. The infrared region can be subdivided into three categories based on their wavelength: near (0.79-3 μm), medium (3-6 μm), far (6-15 μm) and extreme (15-100 μm). The far and extreme regions are together called long wave. The infrared region can be further divided into two categories based on their radiation properties: the reflected (0.7-3.0 μm) and the thermal (3.0-100 μm). Thermal imaging is a technique used for converting a thermal radiation pattern, which is not visible to the human eye, into a visual image (Paritosh *et al.*, 2006). Infrared camera is used to obtain the thermal visual image by transforming energy radiated from object into an electronic video signal. Infrared camera creates images based on the heat energy emitted by the object rather than light reflected off it. The energy emitted by the object is mainly a function its surface temperature. The infrared camera can be classified into three types based on the operation range of wavelength: short wave camera, medium wave camera and long wave

Figure 1: Infrared Region of Electromagnetic Spectrum



camera. The thermal image obtained from the infrared camera can be used for the quantitative analysis of defect location, sizing and characterisation. Infrared techniques can be mainly classified into two types based on the temperature difference generated to obtain thermal image: passive thermography and active thermography. The passive thermography is used for the objects which are naturally at the higher temperature than ambient while in the case of the active thermography, an external heat source is introduced to obtain relevant temperature difference. In active thermography, various modes of thermal simulations are available: pulsed thermography, step-heating, lock-in thermography and vibro-thermography. In this work, delaminations in the composite laminate plates are analyzed by active thermography by recording the temperature profiles on the outer surface of the specimens. In the present experimental process, a constant heat was applied using hot air blower and the increase of surface temperature distribution is monitored and recorded using infrared camera. An abnormal temperature profile could essentially indicate the location of delamination (Maldague, 2002).

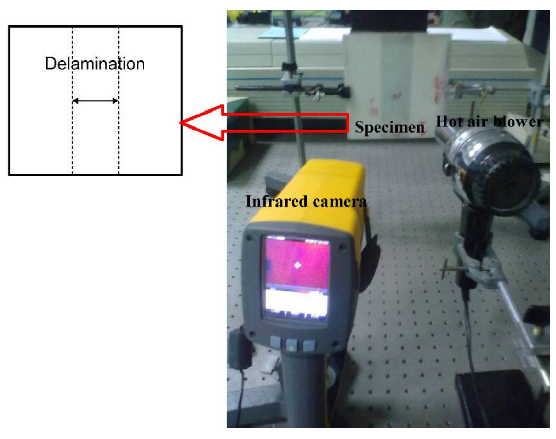
EXPERIMENTS

Depth of Delamination

Sample Preparation and Active Thermography Experimental Setup

A glass fibre reinforced polymer square specimens were fabricated including artificial delamination located at two different depths during the manufacturing process using thin Aluminum foil in order to simulate delamination. The areas of these three specimens were 205 $\times$ 205 mm^2 and the number of layers is 8. Thickness of each layer is approximately 0.3125 mm (total thickness 2.5 mm). Delamination depths for sample 2 and sample 3 were embedded foil in various depth 0.3125 and 1.25 mm from observation side and the area of delaminations was 60 $\times$ 205 mm^2. A hot air blower with 2.5 kW output power was used as heat source. A switch control was applied to control the heating duration from the hot air blower. Specimens were activated by short pre-heating time 7 seconds. The investigation is about observing the temperature distribution of the surface with subsurface delamination during cooling-down process. Specimen's surface temperature during cooling down process was observed in area above delamination and in area without delamination. The specimens were located at a constant distance of 30 cm from heat source and the camera is held 70 cm from the sample. Together with the end of the pre-heating process, the surface temperature was recorded and the delamination appears. The inspection setup presented in Figure 2 uses a

Figure 2: Experimental Set Up for Active Thermography



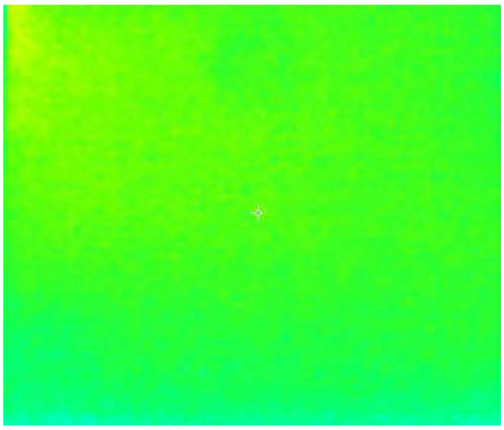
Fluke Ti20 infrared camera. It has an un-cooled detector with focal plane array 128X96HV, where infrared detector absorbs the infrared energy emitted by the studied specimens and converts it into electrical signal.

RESULTS AND DISCUSSION

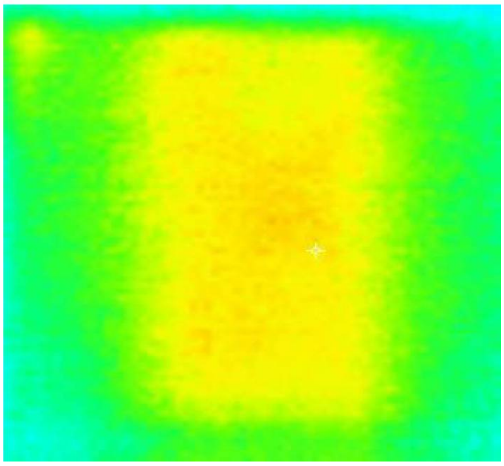
In the present experiment, active infrared thermography was applied to evaluate the ability of non destructive thermography test to detect the delamination in laminate composite material structure with different depth locations. The depth of the simulated delaminations was varied and keeping the area and thickness of artificial delamination same. Generally when the heat was applied from hot air blower to the sample surface, the uniform temperature rise was observed on the surface, if the sample has no delamination. If the sample has delamination on the contrary, a localized high temperature region appears on the sample surface just above the delamination due to the insulation effect of the delamination. The shape of the high temperature region reflects the delamination shape under the surface due to the temperature difference. The temperature images using active thermography for samples 1, 2 and 3 were shown in Figure 3 respectively after a period of 7 seconds of heating. Delaminations in samples 2 and 3 are observed at different times (2 seconds and 3.5 seconds) after ending the preheating stage with different contrast. Due to the surface heating by active thermography, heat propagates from the surface to the rear side. Delamination, as thermal barriers, stop heat diffusion and reflect the heat back to the surface, which results in higher temperature at delamination than in non-defected region.

Figure 3: Temperature Images Using Active Thermography

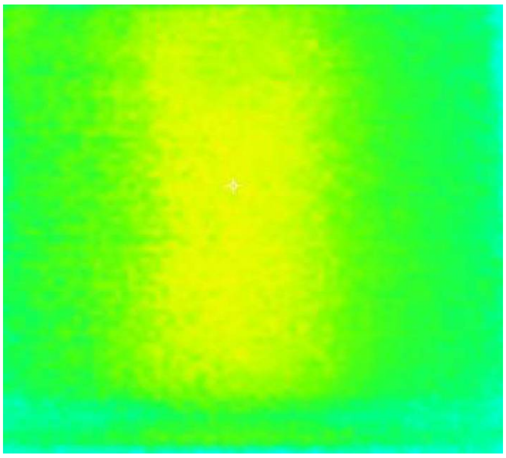
a) Sample 1 (Healthy Plate)



b) Sample 2 (Delamination Beneath One Layer with Depth 0.3125 mm)



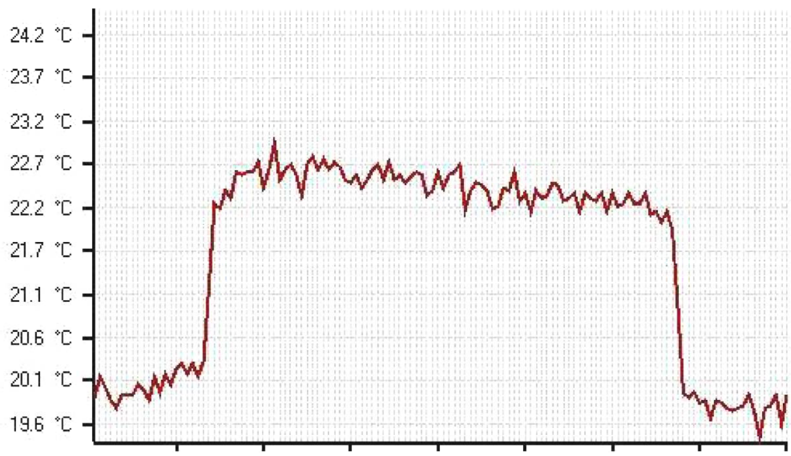
c) Sample 3 (Delamination Beneath Four Layers with Depth 1.25 mm)



In all defected thermograms, highlight the delamination in the composite plates depends on their depth positions, but with various contrast. Obviously the temperature difference between delaminated zone and healthy one are strongly depending on depth of delamination from observation side and thermal conductivity of the delamination. Figure 4a shows that the temperature was almost uniform throughout the surface of healthy plate. While, Figures 4b and 4c show the temperature profile on the surface, with internal delamination. The temperature profile of this delamination during the cooling phase verifies with the characterizing conditions of the delamination. The average thermal contrast obtained from experiment was 0.24 °C for sample 1, where the delamination was 0.3125 mm deep from the outer surface for sample 2 the thermal contrast was 5 °C, where as the delamination at 1.25 mm depth for sample 3 produces a thermal contrast of 3.75 °C with a decrement of 1.25 °C.

Figure 4: Surface Temperature Profiles

a) Sample 1 (Healthy Plate)



b) Sample 2 (Delamination at Depth 0.3125 mm)

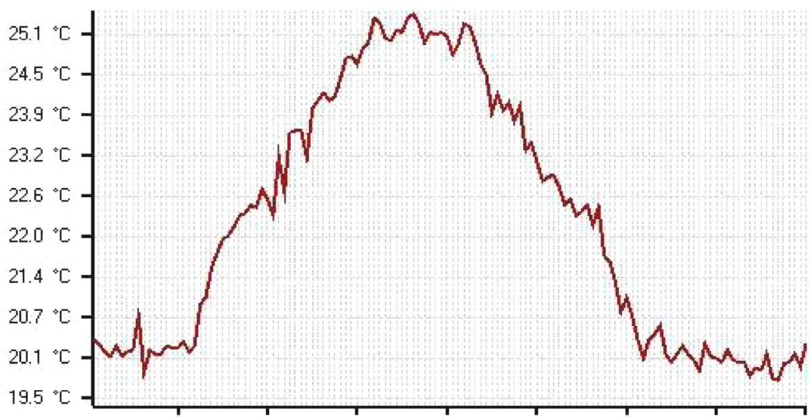
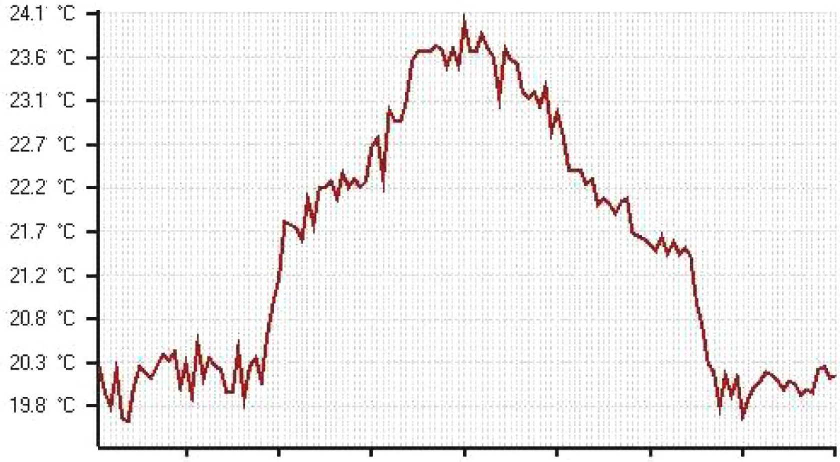


Figure 4 (Cont.)

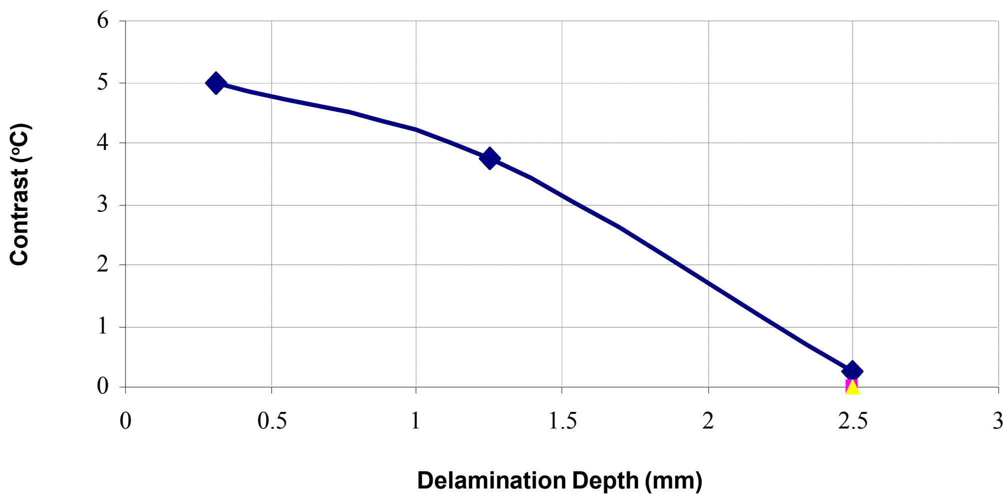
c) Sample 3 (Delamination at Depth 1.25 mm)



Therefore, it can be concluded that an increase in depth of delamination produced a reduction in the thermal contrast as shown in Figure 5. Present experiment reveals that the delamination nearer the thermal camera was identified quicker with increased thermal contrast but that delamination nearer the inner wall of the plate was identified later with a reduced thermal contrast.

Also by comparing the thermal images contain delamination as shown before in Figure 3, the whole length of delamination in samples may not be clear enough, because the thermal image was strongly influenced by the non uniform heating due to short time of heating and sometimes it leads to misinterpretation of results, for this reason the method was adequate especially for detection

Figure 5: Variation of Thermal Contrasts with Delamination Depth



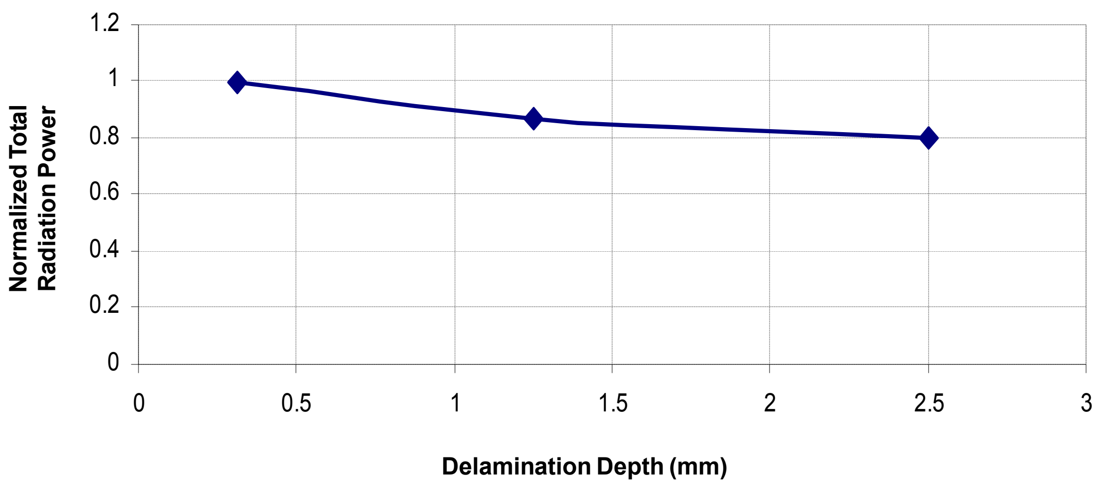
of the near subsurface delamination. Also this technique cannot distinguish whether the effect was real or due to the potential error sources linked to the object, the environment and the acquisition system. The total power emitted by samples 2 and 3 can be theoretically calculated by using Stefan's law, also the total emitted power can be extracted from the resulting experimental curves Figure 4, where the area under the curves proportional to the total radiation power. The relation between total radiation power and depth of delamination shown in Figure 6.

Thickness of Delamination

Experimental Set-Up and Specimens Preparation

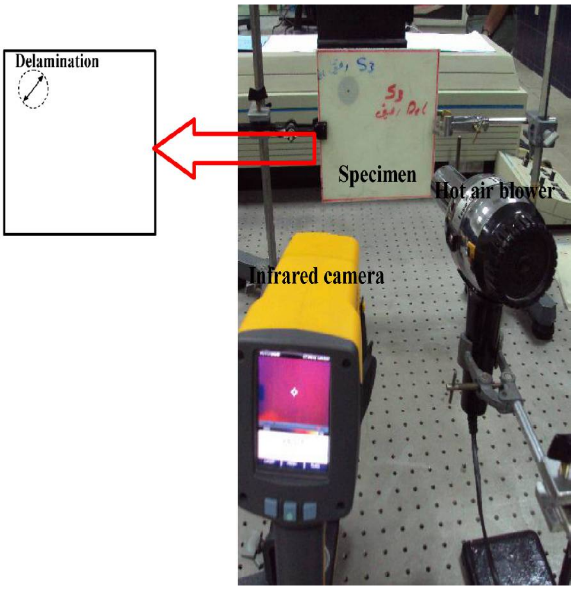
Plates of eight layers include E-glass fibres embedded in an epoxy matrix were manufactured with artificial circular Aluminum foil delamination of diameter 38 mm with different thickness, embedded at the same depth 0.9375 mm (under the third layer of lamination). Sample 1 contains delamination of thickness 0.6 mm and sample 2 contains delamination of thickness 0.1 mm. Both specimens were, square 200 × 200 mm^2 and 2.5 mm thick. The experimental setup for active infrared thermography of composite laminate plate was shown in Figure 7. The infrared camera Fluke Ti20 is the main part here which measures the thermal transient at the surface of the plates resulting from the heating of the plates using an external stimulus source hot air blower of 2.5 kW. An emissivity adjusted to value of 1 in order to eliminate spurious reflections from radiant emitters such as overhead lights or human bodies and to ensure consistency in the sample surface emissivity. The thermal imaging camera was placed at 70 cm from the specimen and heat source kept at distance 30 cm. Specimens were activated by short pre-heating time 7 seconds. The investigation was about observing the temperature distribution of the surface with subsurface delamination after short heating by hot air blower. Specimens were searched during cooling-down process. Specimen's surface temperature during cooling down

Figure 6: Variation of Total Radiation Power with Delamination Depth



process was observed in area above delamination and in area without delamination. Together with the end of the pre-heating process, the surface temperature recording procedure began by using infrared camera Fluke Ti20.

Figure 7: Active Thermographic Inspection Set Up

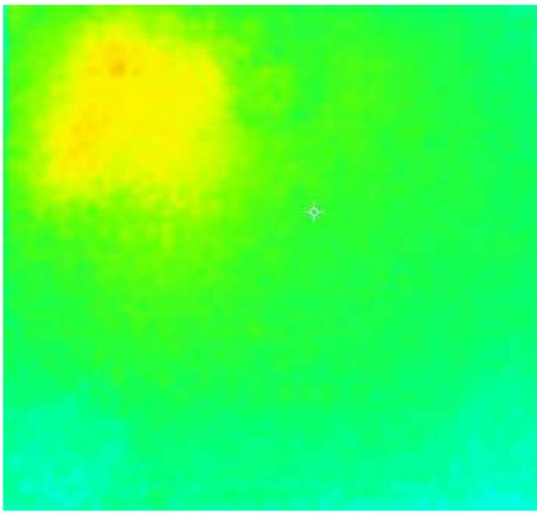


RESULTS AND DISCUSSION

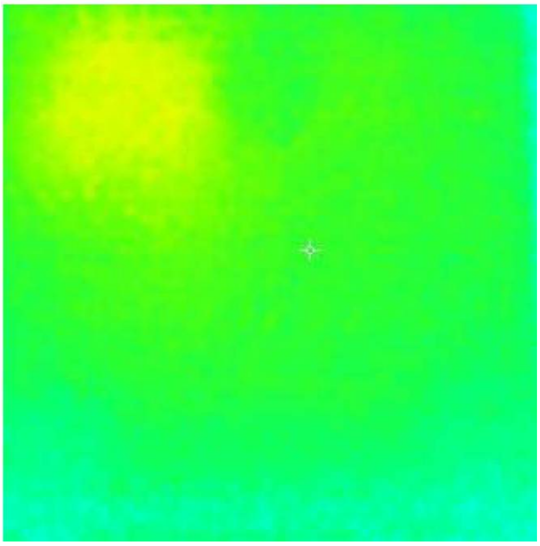
The surface temperature distribution images over the composite laminate plates were obtained at the end of heating time 7 seconds using experimental set-up. The thermal contrast value was measured by thermography to detect delamination which was used to analyze for varying thickness. The thickness of simulated delamination in sample 1 was six times as delamination thickness of sample 2. Herein present experiment the active thermography reflection method was used, meaning that the thermal source and the infrared camera were located on the same side of the specimen. In this case, the delamination zone appeared like a hot spot as shown in Figure 8.

Figure 8: Thermal Images for Sample 1 and Sample 2

a) Sample 1 (Circular Delamination with Thickness 0.6 mm)



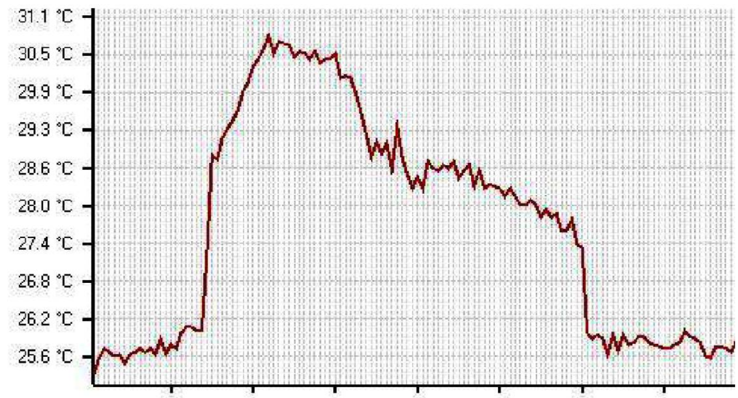
b) Sample 2 (Circular Delamination with Thickness 0.1 mm)



Therefore, the thermal contrasts obtained from experiment (Figure 9) at the place of delaminations of samples 1 and 2 are taken into consideration and were plotted as shown in Figure 10. The Figure revealed that, the thermal contrast value at the delamination of sample 1 was greater than that of sample 2.

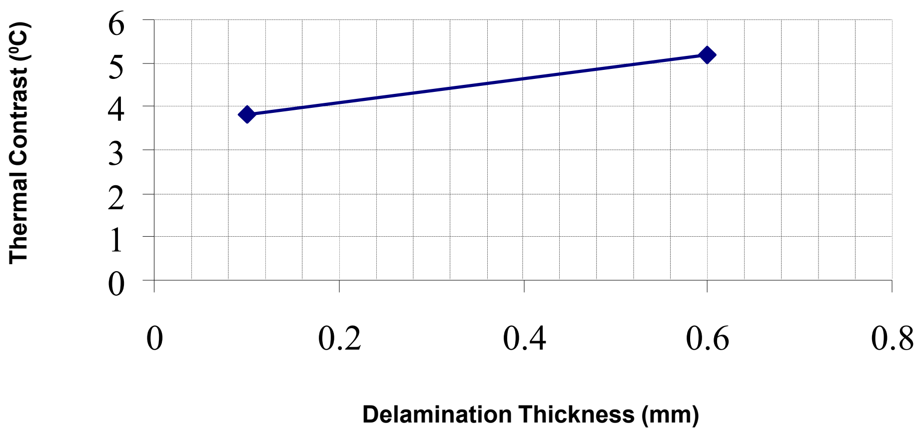
Figure 9: Surface Temperature Profiles

a) Temperature Profile of Sample 1 (Delamination Thickness 0.6 mm)



b) Temperature Profile of Sample 2 (Delamination Thickness 0.1 mm)

Figure 10: Variation of Thermal Contrasts with Delamination Thickness in Sample 1 and Sample 2



Due to the difference in thermal resistance of delamination, the thermal contrast values obtained were 5.2 °C and 3.8 °C, for sample 1 and 2 respectively. As the thickness of delamination increases the thermal resistance of the delamination is increases. This results in higher thermal contrast at the location of thicker delamination.

CONCLUSION

The obtained experimental results allow extracting the following conclusions:

- Radiation heating and thermographic images analysis is an effective method for revealing delamination in the composite materials. It is possible to see the delamination on thermographic image, but the determination of their geometry and position is restricted and not very precise.
- In case of thermographic methods it is not possible to detect delamination after long time of pre-heating of the studied material.
- The thermal contrast changes above delamination quickly, thus temperature measurement must be completed during a short elapsed time after the pulse heating especially for the detection of smaller delamination.
- Thermography methods require specific skills to achieve good results in delamination detection especially for composite materials.
- The infrared thermography is useful in detecting invisible defects non-destructively, extensively and safely.

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