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Scanning Induction Thermography (SIT) on damaged Carbon-Fiber Reinforced Plastics (CFRP) components

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Abstract

Scanning Induction Thermography (SIT) combines both Eddy Current Technique (ECT) and Thermographic Non-Destructive Techniques (TNDT) [1,2]. This NDT technique has been earlier demonstrated for metallic components for the detection of cracks, corrosion, etc. [3-9] Even though Carbon-Fiber Reinforced Plastics (CFRP) has a relatively less electrical conductivity compared to metals, it was observed that sufficient heat could be generated using induction heating that can be used for nondestructive evaluation using the Induction Thermography technique. Also, measurable temperatures could be achieved using relatively less currents, when compared to metals. In Scanning Induction Thermography (SIT) technique, the induction coil moves over the sample at optimal speeds and the temperature developed in the sample due to Joule heating effects is captured as a function of time and distance using an IR camera in the form of video images. A new algorithm is also presented for the analysis of the video images for improved analysis of the data obtained. Several CFRP components were evaluated for detection of impact damage, location of stiffeners and disbonds using the SIT technique.

1. Introduction

CFRP composites attract increasing attention for use in load-bearing components particularly in the aerospace industries. The major advantage of thermography over other techniques is the potential for the rapid inspection of a large area within a short time. SIT is a new hybrid, non-contact and non-destructive technique which uses induced eddy currents to heat the material being tested and defect detection is based on the changes of the induced eddy current flows revealed by the thermal contrast captured by a Medium Wave Infrared (MWIR) camera. The presence of anomalies, and the characteristics of the materials, change the surface temperature and thus can be used for the non-destructive evaluation.

In this paper a new algorithm for processing the raw data has been developed to account the time delay occurred during heating due to the motion of coil from one end to the other end. This algorithm is based on maximum temperature attained by each pixel. As this study is conducted on composites, the temperature developed on the sample surface will be high compared to the coil temperature which makes this algorithm work perfectly for composites. For metal samples, the temperature developed on the surface will be less than the coil temperature which makes the improper functioning of this algorithm. There we need to take care of the coil temperature as well.

2. Experiment setup and test procedure

In this experimental work, an impact-damaged (Impact energy= 13 J) CRFP panel (280 x 280 mm^2) of 3 mm thickness and an aircraft component were investigated. The setup consists of a solid-state induction heating system that converts single-phase line voltage to a 1 kW output over a range of radio frequencies and voltages. This energy is delivered to a remote series-resonant circuit-including the coil-where a precisely controlled magnetic field is created around the sample. The coil is mounted on a single axis scanner whose speed can be precisely varied. Experiments have been carried out in reflection mode, where the infrared camera and the induction coil are on the same side. Figure 1 shows the experiment setup.

3. Impact damage in composite material

3.1. Introduction

Damage caused by low-velocity impacts is a serious concern in aircraft industries. Such impacts are unavoidable in normal aircraft operations. In case of metal structures, impact damage is not generally considered to be a threat owing to the

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ductile nature of metals. Metals can absorb large amounts of energy. But in case of composites, as they are brittle in nature, they can absorb energy only in elastic deformation and through damage mechanisms and not via plastic deformation [10]. A low energy impact can be caused by a number of ways. Falling of a hand tool on to a composite surface during subsequent servicing operation, runway debris thrown up by aircraft wheels during take-off or landing, collision with birds, hail stones etc., are some of the ways through which impact damage can be caused on the composite surface. This remains little or no sign of the damage at the surface [11]. The damage caused due to impact may eventually lead to component failure. The heterogeneous and anisotropic natures of composites give rise to four major modes of failure. They are matrix mode, delamination mode, fiber mode and penetration [10]. So the inspection of vulnerable surfaces at regular intervals is inevitable to avoid catastrophic failures. Conventional ultrasonics scanning can detect this kind of damage but inspection of huge area makes this technique difficult to implement. SIT provides fast and non contact scanning of the surface and readily gives the damage information.

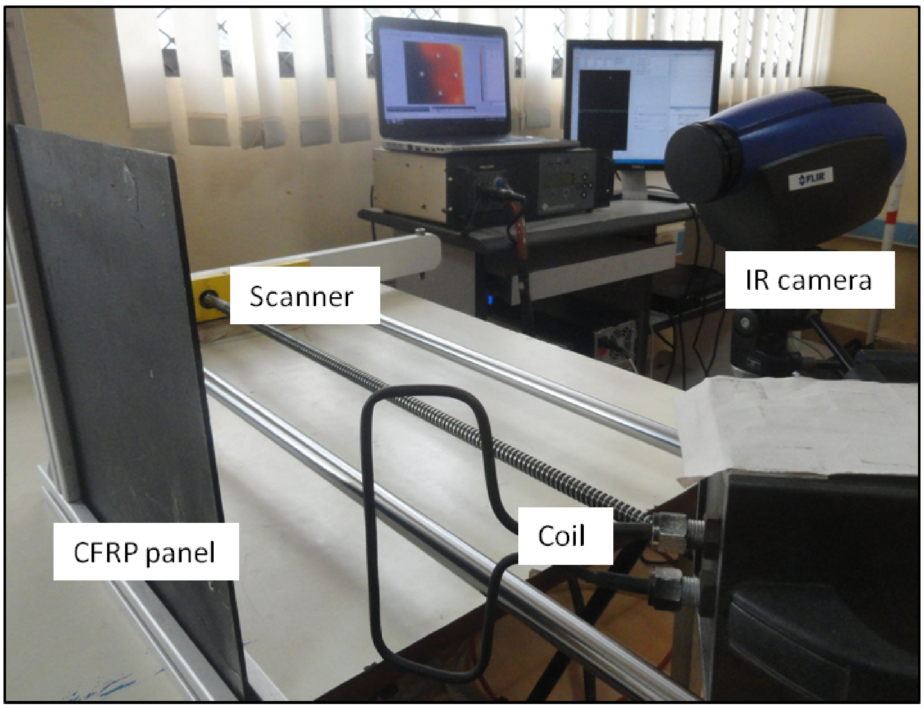

Figure 1. Experimental setup

3.2. Experimental work

In this work, impact-damaged CFRP panel (280 x 280 mm^2) of 3 mm thickness impacted with 13 J energy is investigated. Figure 2 shows the real image of CFRP panel. By keeping the sample stationary, induction coil is moved along the surface with an offset distance of 3mm at a speed of 50 mm/s. Measurements have been done in reflection mode using a Medium Wave Infrared (MWIR) camera with a frame rate of 100 Hz. Experiments were carried out for different sample orientations - 0^o, 90^o, ±45^o. A schematic diagram of different orientations of sample is shown in figure 3. The induction coil is moved from right to left.

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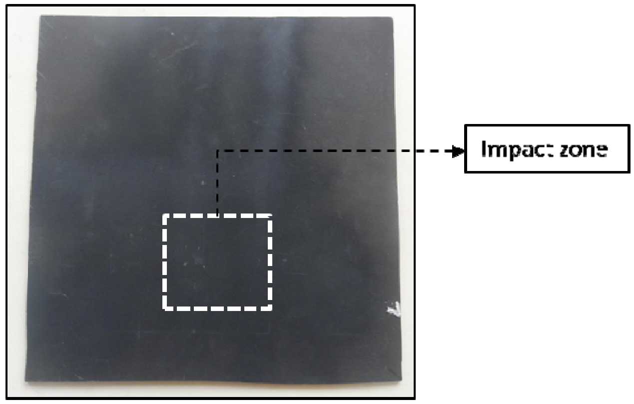

Figure 2. Real image of CFRP panel. The impact zone is shown in the image

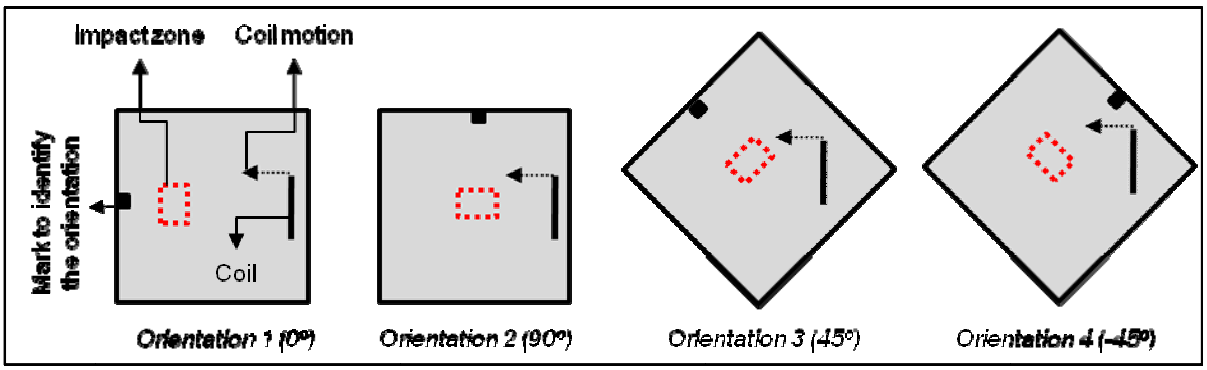

Figure 3. Different specimen orientation for performing SIT

3.3. Scanning Induction Thermography

SIT technique is performed on the sample for different sample orientations. As the coil moves along the sample, temperature of the sample is increased and it is recorded by an infrared camera in reflection mode. Figure 4 shows the thermal images obtained by scanning the sample which is kept at different orientations. The frames shown in Figure 4 are chosen in such a way that defects are clearly visible. The induction coil can be seen in the left side of the thermal image. Depending up on the sample orientations, defects picked are also oriented differently. In order to visualize the defect irrespective of sample orientation, an image processing algorithm has been developed which is discussed in the next section

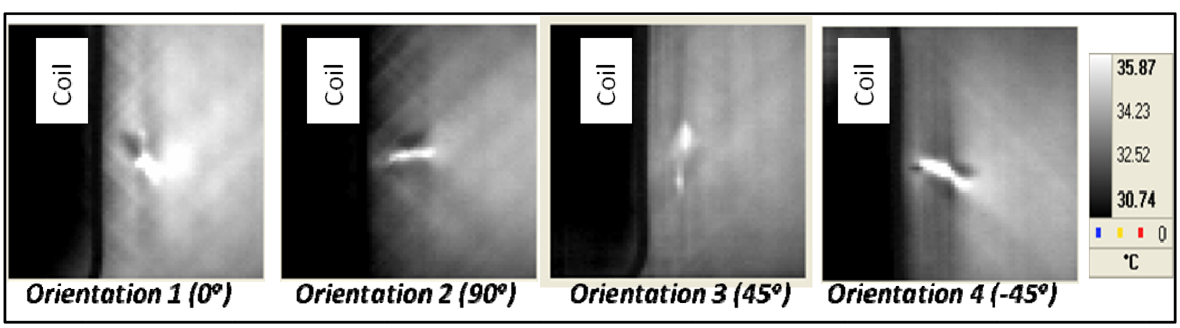

Figure 4. Thermal images obtained by scanning the sample which is kept at different orientations

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3.4. Image processing algorithms

3.4.1. Maximum Temperature offset algorithm

Due to the movement of the coil, the maximum temperatures attained by the pixels along the direction of coil movement will be at different times which make the comparison difficult. Figure 5 shows a thermal image where a few points are selected along the direction of coil motion and figure 6 shows the temperature vs. time plot for these points. In order to account this variation in heating time, an image processing algorithm has been developed in MATLAB® by keeping maximum temperature attained as a reference point. The algorithm is as follows:

- Found the frame corresponding to maximum temperature developed for each pixel
- Temperature information from that frame till end is obtained
- This is repeated for all pixels
- A new image sequence is generated by keeping maximum temperature value of each pixel in first frame and the rest of the information in the following frames
- The generated image sequence corresponds to a uniform heating of composite surface

A schematic diagram of the algorithm is shown if figure 7. Figure 8 shows the first frame of newly generated image sequence for all the sample orientations. Defect is clearly visible in the shown images

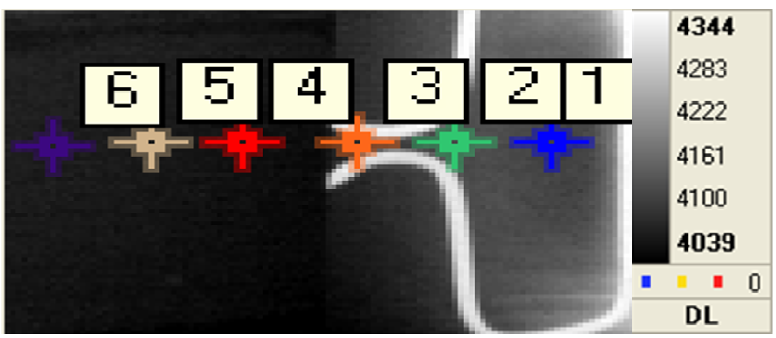

Figure 5. Thermal image showing different selected points

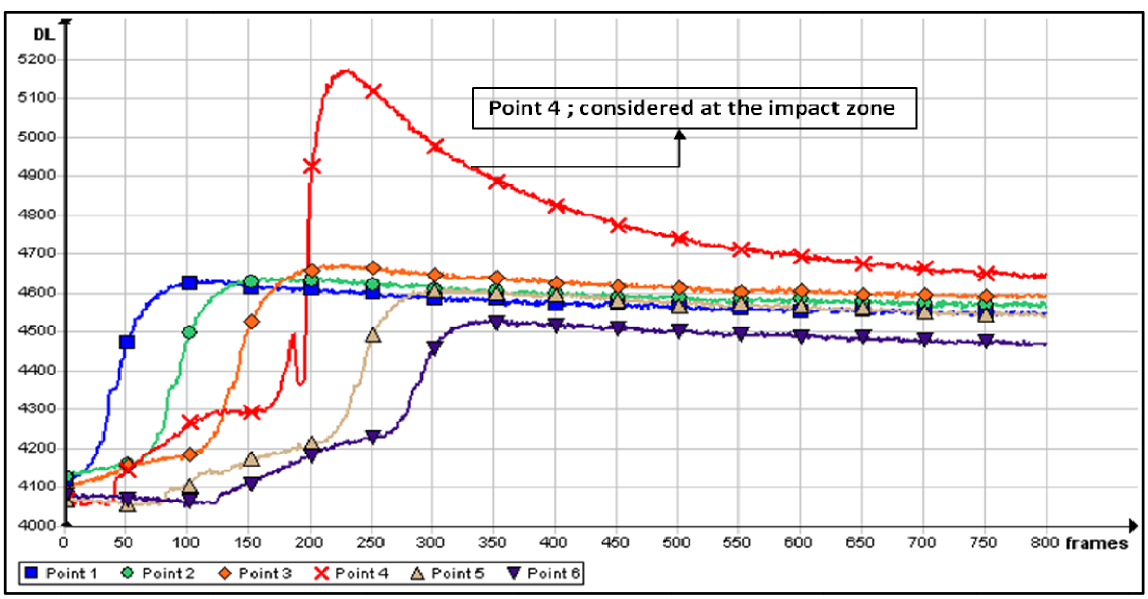

Figure 6. Temperature vs. Time plot for different points

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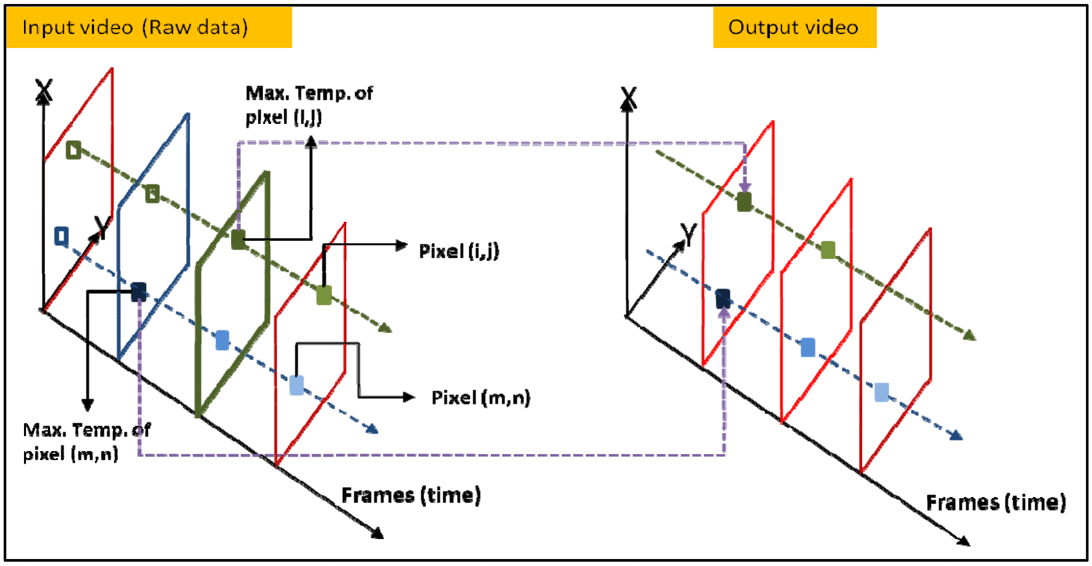

Figure 7. Schematic diagram of maximum temperature offset algorithm

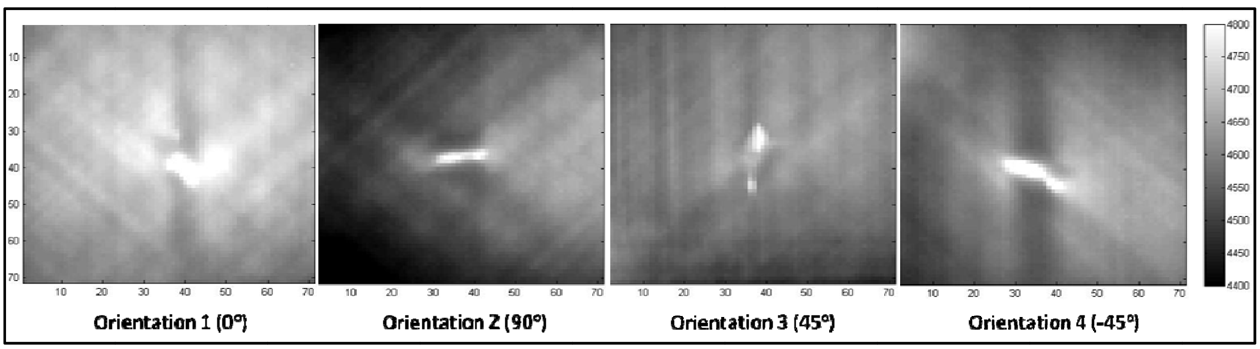

Figure 8. First frames of newly generated image sequence for all the sample orientations

3.4.2. Image merging and rotation algorithm

Depending upon the sample orientations, size and orientation of identified defects are different. In order to visualize the damage caused due to impact irrespective of sample orientation, an image merging and rotation algorithm has been developed in MATLAB®. In this, a reference point is identified on all the four thermal images and rotation and merging are performed with respect to this point. Orientation 1 (0^{o}) shown in figure 3 is set as the reference orientation to which all other images are rotated. Figure 9a shows the final image obtained by rotating and merging all the four images. Figure 9b shows the ultrasonics scanning result of impact damaged zone.

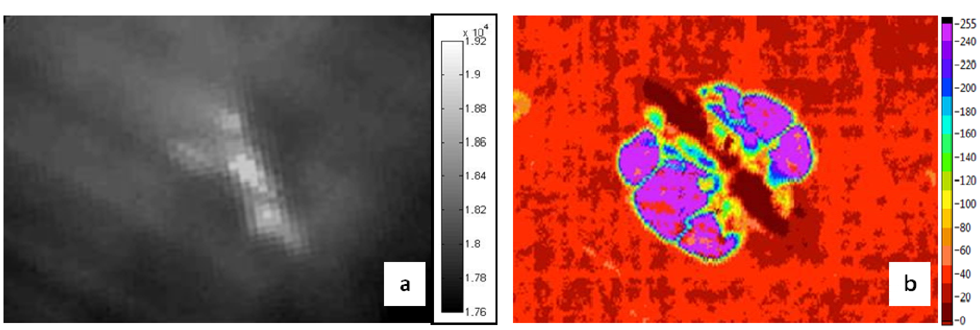

Figure 9 a: Final image obtained by rotating and merging all the four images; b: Ultrasonic scanning result of impact damaged zone

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The size and the orientation of the impact damage in the composite plate are clearly reflected in thermal image obtained by SIT. This technique has been shown to be effective for detecting and imaging crack like defects introduced on the sample due to impact. From the thermal image shown if figure 9a it can be clearly seen that the temperature developed at the impact zone is higher than the non impact zone. Figure 6 shows the temperature time plot of certain points on the thermal image. Point 4 in figure 6 is taken at the impact zone and we can observe a temperature hike in that point compared to other considered points. Increase in temperature at the impact zone can be considered as the region having more concentration of eddy currents due to fiber breakage. Where ever any discontinuity is there, eddy currents will trace the least resistive path to complete the loop resulting in high concentration of eddy currents at discontinuity. High concentration of eddy currents results in more heating. This behavior is an indication of fiber breakage due to impact and it is clearly imaged using SIT which is difficult to obtain in other conventional methods.

4. Scanning on aircraft component

An aircraft component made of CFRP (1200 X 500 mm^2) is investigated using SIT. Figure 10 shows the real image of scanned component. By keeping the component stationary, induction coil is moved along the surface with an offset distance of 3 mm at a speed of 40 mm/s. Measurements have been done in reflection mode using a Medium Wave Infrared (MWIR) camera with a frame rate of 100 Hz. As the induction coil length is small compared to component width, the whole area is divided into 3 regions and scanning is performed over these regions (figure10). The induction coil is moved from right to left.

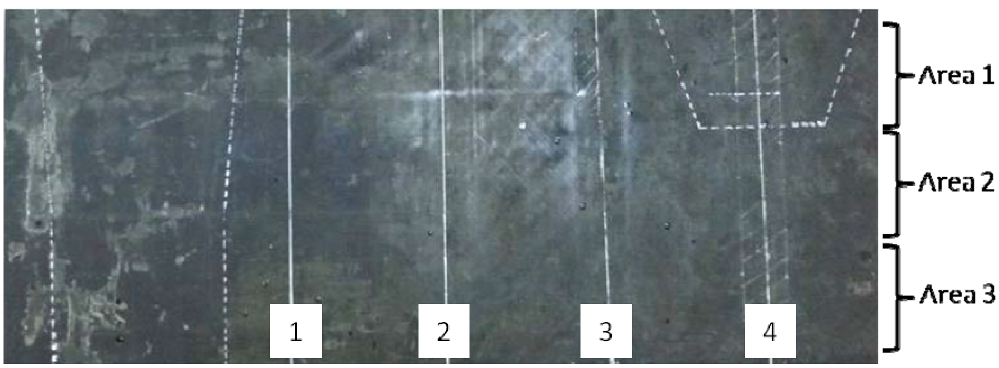

Figure 10. Real image of scanned aircraft component. Locations of stiffeners are marked as 1, 2, 3 and 4; Scanned regions are marked as Area 1, Area 2 and Area 3.

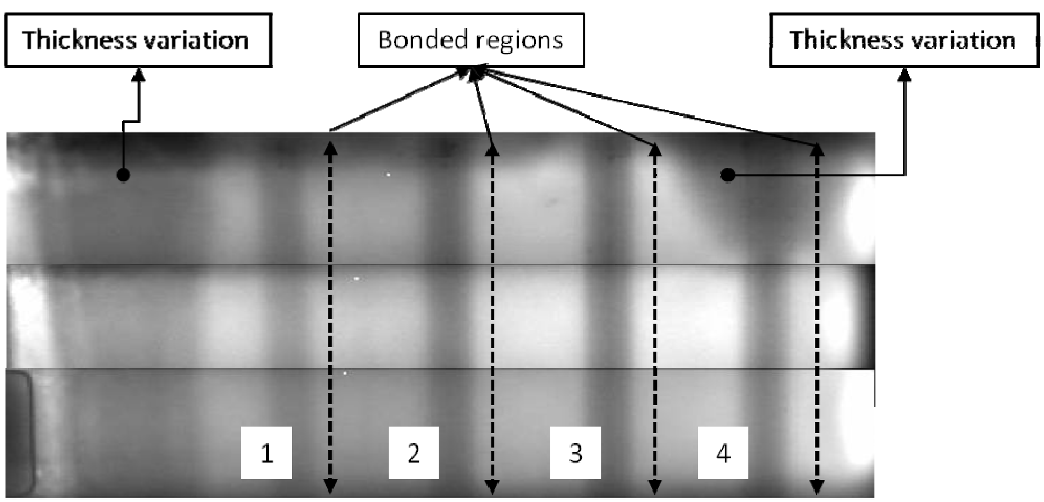

Figure 11. Thermal image of aircraft component obtained after scanning

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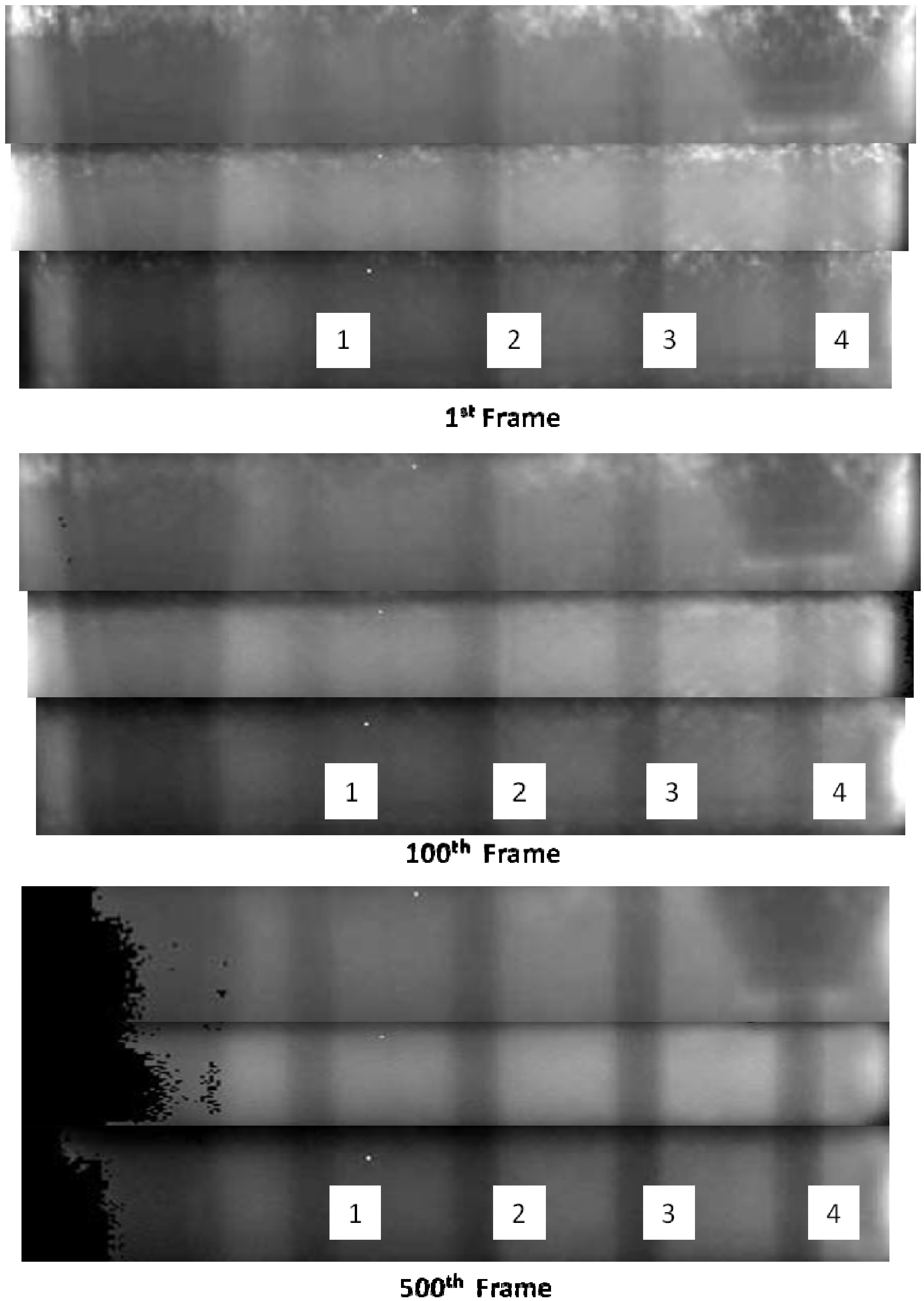

Figure 12. The 1st, 100th and 500th frames of newly generated image sequence

Figure 11 shows the thermal image obtained using SIT technique after the scanning has performed. The induction coil is visible in the left side of the image. The hidden stiffeners and thickness variations are clearly visible in the thermal image. From the thermal image we can identify four stiffeners which are dark in colour, thickness variations at right top corner and left edge. While at the other regions of the component we can observe an almost uniform thermal contrast which can be inferred as uniform thickness region. Maximum temperature offset algorithm which is explained in section 3.4.1 is

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also used here to account variation in heating along the surface. The 1st, 100th and 500th frames of newly generally image sequence are shown in Figure 12**.** From this generated image sequence some additional information are getting regarding the bonding between stiffeners and surface. In the raw thermal image, the four stiffeners' regions have almost uniform thermal contrast. But in the newly generated image sequence these regions do not have same kind of thermal contrast. The reason for this difference is the time delay in heating the fourth stiffener with respect to first stiffener. In the newly generated image sequence the first and the fourth stiffeners are barely visible in 1st and 100th frames and it is enhanced in the 500th frame. The reason might be the slow diffusivity of generated heat due to lack of proper bonding between stiffeners and surface. These defective bond regions are taking more time to take away the heat from the surface compared to good bond regions (second and third stiffeners regions).

5. Conclusions

The main objective of this work was to study the feasibility of Scanning Induction Thermography (SIT) on composites to assess various defects. Using this hybrid technology we could clearly identify the crack like defects such as fiber breakage during impact, fiber matrix separation etc, presence of stiffeners, strength of bonding between surfaces and other thickness variations (from 2.5 mm to 5 mm). In figure 4, even the fiber orientations were found to be imaged. The main advantage of this technique is that it investigates large areas with short span of time and is extremely sensitive to defects that have footprint at orientations perpendicular to the plane of the surface. Also, by orienting the coil in appropriate directions, the orientation of the flaw can be imaged. In addition, complex contoured components can be examined using coils that are configured to match the shape of the component, thereby ensuring the quality assurance of such components. However it must be noted that the multiple delaminations caused due to impact (that is visualized using immersion ultrasonic C-scan in figure 9b) could not be identified using this technique. This could be due to the penetration of the EM fields through these delaminations. However, more detailed analysis of the data using numerical models is underway to ascertain the feasibility of detection of delaminations in composites using this method. Also, the excess heating at edges leads to difficulties during inspection of these critical regions. This edge heating can be predicted and algorithms for analyzing data from such regions must be developed in order to extend this technique to such regions.

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