THERMOGRAPHIC INSPECTION OF POLYMER MATRIX COMPOSITE LAMINATES SUBJECT TO IMPACT DAMAGE

[1] Tarpani J.R., jrpan@sc.usp.br
[1] Almeida E.G.R., euripedes_almeida@yahoo.com.br
[1] Simêncio E.C.A., ecasime@sc.usp.br
[1] Mota L.P., lucasponez@usp.br
[1] Paz J.H.A.A., jaimehilariopaz@gmail.com
[1] Gualberto A.R.M., alan@cdcc.sc.usp.br
[1] Cardoso F.L.A., felipe.usp@gmail.com
[1] Razzino C.A., crazzino@sc.usp.br
[1] Gatti M.C.A., mcristina_gatti@hotmail.com
[2] Milan M.T. milan@mib.eng.br

[1] Escola de Engenharia de São Carlos, Departamento de Engenharia de Materiais, Aeronáutica e Automobilística, Av. Trabalhador São-Carlense, 400, Pq Arnold Schimidt, 13566-590, São Carlos - SP, Brazil, Phone +55 16 3373 9591, Fax +55 16 3373 9590
[2] Instituto de Materiais do Brasil (MIB), R. Paulino Botelho de Abreu Sampaio, 881, Jd Bethânia, 13561-060, São Carlos - SP, Brazil, Phone/Fax +55 16 3376 1863

Abstract. *Thermoset and thermoplastic polymer matrix composites were impacted with different energy levels. The damaged laminates were evaluated by active infrared thermography in transmission mode. Thermograms from the thermoplastic matrix laminate showed more clear and delineated damage indications as compared to the thermoset matrix composite images. The convective heating of the samples by hot airflow was more efficient than via radiation, using filament lamp. Longer heating times improved damage visualization, whereas the positioning of the specimen´s impacted surface regarding the infrared camera and the heating source did not affect the thermograms quality. It has been concluded that infrared thermography is a simple, robust and trustworthy methodology for detecting impact damages as slight as 5 Joules in composite laminates devised to aeronautical application.*

Keywords*: Impact damage; Infrared thermography; Polymer composite laminates.*

1. INTRODUCTION

1.1 Infrared Thermography

Infrared thermography (IRT) is a nondestructive testing technique based on the component's thermal mapping (thermographic imaging) to locate damaged or defective regions. This is possible because thermal conductivity, or conversely, thermal resistivity strongly depends on the integrity of the material. Essentially, a thermogram shows the differences on the local temperature of the component as color gradient patterns or shades of gray. The main advantages of IRT methodology are: fast inspection, non-contact technique, real-time image interpretation and non-lethal radiation. The few method's disadvantages are: the inspected component must be relatively thin, and the relatively high investment. In the last decade, IRT has benefited the aircraft industry with reduced inspection costs during the manufacture and periodic aircraft maintenance stages. Furthermore, IRT has proven capable of providing reliable results, quite fast and efficiently, regarding the size and location of defects and damages (Maldague, 2001; Avdelidis *et al*, 2004; de Ocáriz *et al*, 2005; Riegert *et al*, 2006; Ray *et al,* 2007).

In the active form of thermography (Swiderski *et al*, 2002; Riegert *et al*, 2007) the assessed object is thermally stimulated (e.g., lamps, flashes, hot airflow, ultrasonic wave, eddy current, microwave and laser) so that an internal heat flow is generated on it. A surface or sub-surface defect or damage causes a disruption of this energy flow, thus leading to a thermal contrast on the component surface, which is detected by a thermographic camera, so that an indication is obtained. During inspection in the active form of thermography, the heating source may be located on the same side of the thermographic camera, concerning the evaluated body, then the reflection mode (single-sided access mode) is designated; conversely, if the heat source is at the opposite side of the camera, with the object situated between them, the so-called transmission mode (dual-sided access mode - Santulli, 2003) is established, as illustrated in Figure 1.

1.2 Polymer matrix composite laminates in the aircraft industry

In recent years, the use of composite materials in the commercial aircraft industry has expanded substantially. A typical example is the new Boeing 787 jetliner, whose weight percentage of composite materials applied to primary and secondary structures reached the unprecedented level of 50%. The polymer (thermosetting or thermoplastic) matrix composite (PMC) laminates are among the most widely used construction materials in this sector. It is roughly estimated that the replacement of traditional metallic alloys for structural polymeric composites, besides the obvious vehicle weight reduction and the consequent fuel saving and increased productivity output, might enable a final cost reduction of up to 25%.

PMC solid laminates, especially those reinforced with continuous carbon fibers, combine high specific mechanical properties (i.e., high strength and stiffness/density ratios), substantially high service temperatures, overall good chemical resistance to solvents, and adequate thermal and dimensional stability even under moisture. However, the shortcoming of this kind of material, in general, is high flammability and low resistance to fire (Resende & Botelho, 2000; Mouritz, 2003).

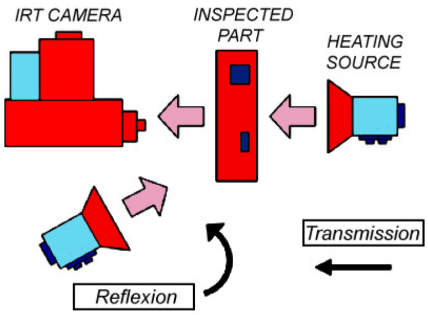

Figure 1. IRT modes in active form of thermography.

1.3 Impact damage in PMC laminates

Structural PMC laminates reinforced with high-performance continuous fibers (e.g., carbon, glass, quartz, aramid) are currently produced by complex manufacturing methods. However, they are still prone to be damaged by transversal impact during (or shortly afterwards) their processing, causing surface or sub-surface discontinuities (e.g., delamination, matrix and fiber cracking) that can jeopardize the in-service performance of the component.

In particular, in-plane compression strength of laminated structures is greatly impaired by delamination-type damage, culminating in low resistance to buckling failure (Freitas and Reis, 1998).

In addition, aircrafts are prone during their lifespan to numerous sources of single or repeated transverse (through-the-thickness) impact events (Figure 2), from low to high energies (Alves *et al*, 2003).

Figure 2. Cloud of birds during an aircraft landing (*source: internet, access 2007*).

This work intends to apply the infrared thermography (IRT) technique as a nondestructive inspection tool for indication and characterization of low energy single impact damage in aeronautical grade thermosetting and thermoplastic PMC laminates.

2. MATERIALS AND METHODS

2.1 Materials

Structural laminates of thermosetting epoxy and thermoplastic polyphenylene-sulphide matrices reinforced with continuous carbon fibers, respectively C-EPX and C-PPS composites, were studied.

The 5 mm-thick C-EPX laminate was fabricated by stacking 24 layers of bi-directional (0/90) 3K eight harness satin (8HS) fabric according to the architecture $[(0/90), (+45/-45)_2, (0/90)]_6$. The 4.75 mm-thick C-PPS composite was produced by stacking 16 layers of bi-directional (0/90) 3K 5HS fabric according to the array $[(0/90), (+45/-45)_2, (0/90)]_4$. The laminates were vacuum bagged and consolidated in autoclave by applying temperature and external pressure.

Rectangular flat specimens with in-plane dimensions of (100 x 150) mm^2 according to ASTM-D7136M (2005) and ASTM-D7137M (2005) were machined from the original plates by Embraer S.A.

2.2 Impact tests

The test specimens were subjected to single transversal impact as per ASTM-D7136M (2005) within the energy range of 5-30 Joules, using a 16 mm diameter steel impactor accelerated to 1-3 m/s. A semi-instrumented pendular Charpy impact testing system was specially adapted to the task, so that the absorbed energy by the testpiece could be promptly determined.

2.3 Thermographic inspection

After the impact tests, infrared thermograms were captured for two different exposure times of the specimen to the heating source, that is, active thermography form was employed. A Flir® infrared camera operating in the temperature range of -20 to 350°C and with nominal sensitivity of 0.1°C to 30°C was utilized, which was positioned in such way that the so-called transmission mode was always guaranteed. Figure 3 illustrates two variants of the technique, in which the impacted face of the specimen is turned toward the camera (here named approach 1) or toward the heating source (approach 2).

Initially, a conventional power filament lamp was used as a heating source in order to generate thermal gradients in the specimen surface. A quite simple wood-made apparatus was employed to hold the specimen perpendicularly to the visible light rays, as shown in Figure 4a.

In the second part of the experiment, the damaged samples were thermally excited by controlled hot airflow produced by commercial hot air blowers. The hot air was blown inside a parallelepiped shaped cardboard box with a volume of approximate 0.1 m^3, which had a lateral opening in which the sample was tightly attached to minimize heat leaking through the gaps (Figure 4a), as suggested by Qin and Bao (1996).

In all cases, the distance between the inspected sample and the thermographic camera was set at approximately 0.5 m.

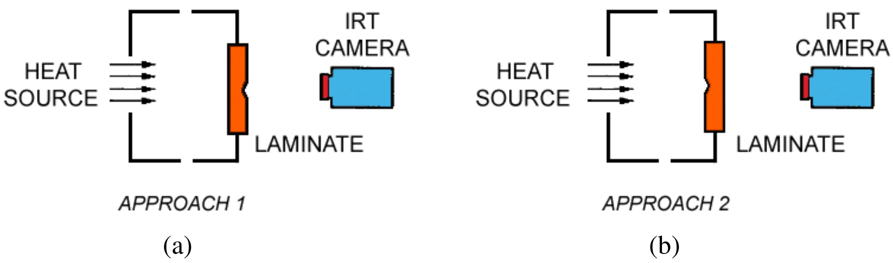

Figure 3. (a) Heating approach 1 - impacted face towards the thermal camera, (b) Approach 2 - impacted face toward the heating source.

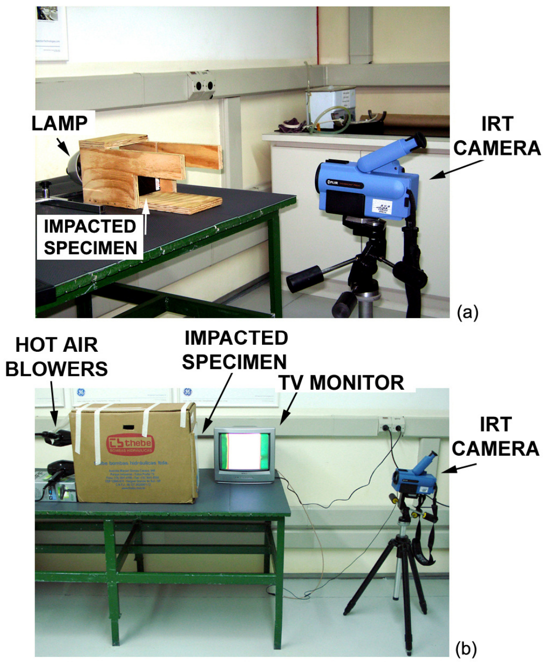

Figure 4. (a) Test set up for tungsten filament lamp as the heater element; (b) Specimen heating with air blower.

3. RESULTS AND DISCUSSION

3.1 Impact tests

Figure 5 shows the impacted surface of the specimens subjected to single impact with energies of 5 and 30 Joules, respectively.

It is promptly concluded that visual inspection of C-PPS is more revealing regarding the impact damage caused in the laminate, since a bigger indentation is created in this high-toughness material, as compared to the thermosetting C-EPX composite. It is indeed an advantageous aspect of C-PPS laminates over C-EPX ones, since walk-around periodic inspection of aircraft is by far the most applied nondestructive method.

However, relying solely on Figure 5 no statement is possible with regards to the damage resistance and tolerance characteristics of both laminated composites evaluated. With respect to the resistance criterion, it is necessary to quantify and, equally important, to qualify both the internal and the rear surface damages impinged to the concurrent laminates. Concerning the tolerance criterion, the post-impact mechanical characterization is essential to determinate the residual resistance of the damaged laminates.

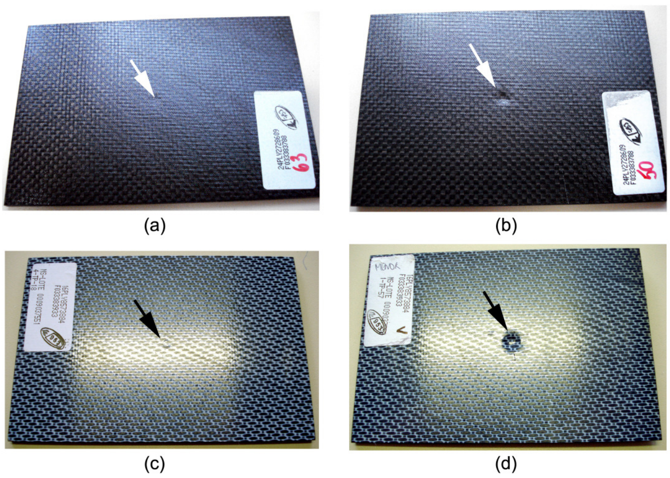

Figure 5. Front face of transversely impacted laminates: (a,b) EPX-C = 5 and 30 Joules, respectively; (c,d) C-PPS = 5 and 30 Joules, respectively.

In Figure 6 the impact testing results are plotted in terms of the absorbed energy versus the energy apportion during the mechanical shock. The experimentally determined data fully corroborate the aforementioned statement in regard to damage resistance of the laminates, since data points reveal that despite the considerable difference between the indentation width and depth in the front face of the C-EPX and C-PPS composites, the absorbed energy levels are very similar and close to the impact energy. This indicates that the fracture mechanisms operating internally and in the rear surface of the laminate, and therefore not visible to the observer, contribute considerably to the consumption of impact energy, and must necessarily be more accurately identified and characterized in order to infer the overall performance of structural composite laminates.

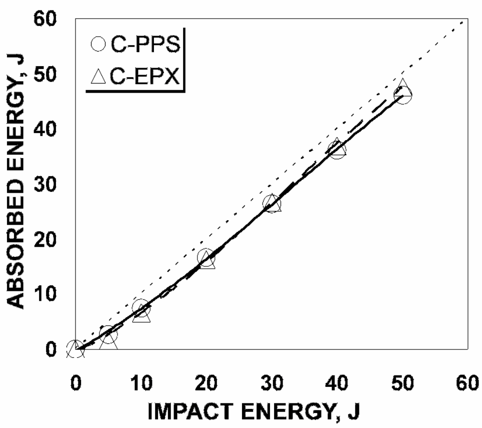

Figure 6. Absorbed energy by the PMC laminates as a function of impact energy.

3.2 Thermographic inspection

3.2.1 Heating by lamp

Figure 7 shows the thermograms obtained by heating C-EPX laminate with filament during a period of time (t_a) of 10 seconds. The results for heating approaches 1 and 2 (see Figure 3) are illustrated for various impact energies previously applied to the thermosetting composite laminate. They indicate that IRT can only clearly detect the impact damage at the center of the specimen from an impact energy of 30 Joules, when a cold spot created by the higher thermal resistivity of the damaged material is unequivocally noted, regardless of whether the heating is performed according to approach 1 (upper thermograms) or 2 (lower ones).

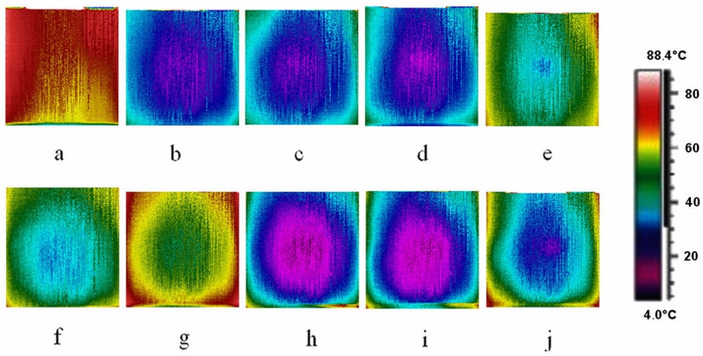

Figure 7. C-EPX thermograms by lamp for t_a = 10 s: (a-e) Heating approach 1; (f-j) Heating approach 2: (a, f) Impact energy = 0 Joules; (b,g) 5 J, (c,h) 10 J, (d,i) 20 J and (e,j) 30 J.

Very similar results were obtained for the C-PPS laminate (Figure 8), also considering t_a = 10 seconds and identical experimental conditions as aforedescribed for the C-EPX composite.

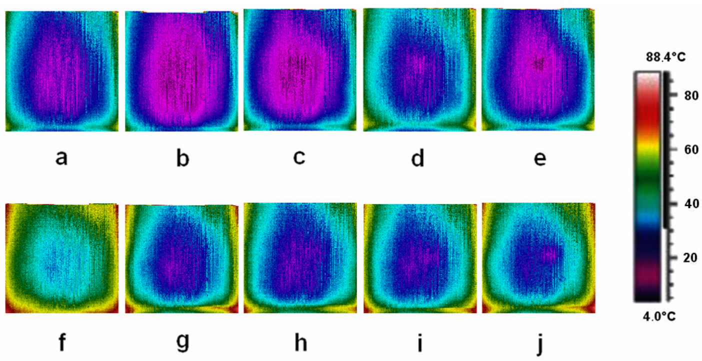

Figure 8. C-PPS thermograms by lamp for t_a = 10 s: (a-e) Heating approach 1; (fj) Heating approach 2: Impact energy = (a, f) 0 Joules; (b, g) 5 J, (c, h) 10 J, (d, i) 20 J and (e, j) 30 J.

Figures 9 and 10 show the thermograms obtained respectively for the C-EPX and C-PPS laminates after a longer heating time by lamp (t_a = 16 s). They essentially show the same results as, respectively, Figures 7 and 8 above. This indicates that, in principle, a shorter heating time of 10 seconds would be enough to detect the damage caused by a 30 Joules impact to both the laminates. However, a more detailed observation of Figure 10, referring to the C-PPS laminate, enables one to infer the signs of damage created by 20 J impact energy, indicating a beneficial effect of a longer heating time for the IRT inspection of the thermoplastic PMC laminate.

The possibility of detecting lower energy impact damages for the C-PPS laminate (20 Joules) as compared to the C-EPX (30 Joules) can be related, somewhat complexly, to both the nature of the polymer matrix (mainly its thermal properties) as well as to the structural changes induced by impact damage, since they directly affect the physical properties of the matrix, fiber and corresponding interface. Furthermore, the trend of the C-PPS composite in forming a larger indentation on the impacted surface than in the C-EPX laminate, for the same incident energy (Figure 5), may also contribute to a more accurate damage indication in the thermoplastic composite, although, as previously mentioned, this external damage, more clearly and promptly identified in the C-PPS material, does not necessarily imply a more significant structural integrity compromise if compared to the thermosetting laminate.

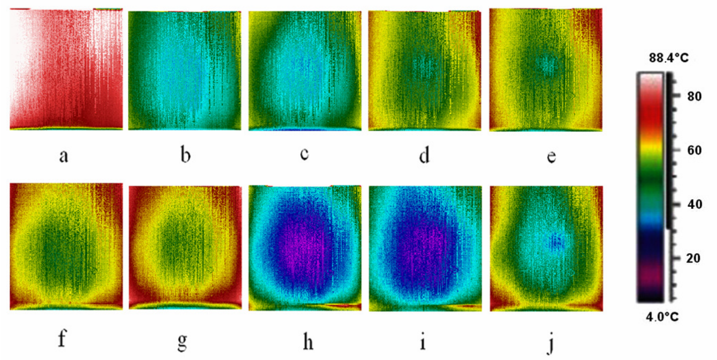

Figure 9. C-EPX thermograms by lamp for t_a = 16 s: (a-e) Heating approach; T (f-j) Heating approach 2: (a, f) Impact energy = 0 Joules; (b,g) 5 J, (c,h) 10 J, (d,i) 20 J and (e,j) 30 J.

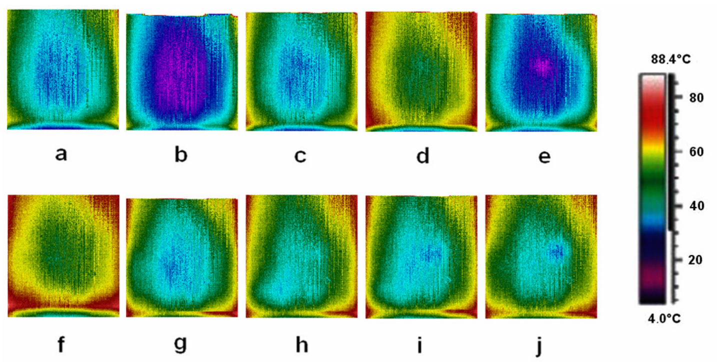

Figure 10. C-PPS thermograms by lamp for t_a = 16 s: (a-e) Heating approach 1; (fj) Heating approach 2: Impact energy = (a, f) 0 Joules; (b, g) 5 J, (c, h) 10 J, (d, i) 20 J and (e, j) 30 J.

A meticulous reader may question why the coloring patterns of the thermograms in Figures 7 and 8 are not the same if identical heating time and conditions were used in the 10 s experiments (the same reasoning applies to the 16 s ones: Figures 9 and 10). Taking as examples the 7g and 7h thermograms (or 9g and 9h), which exhibit very different color patterns, the reason is that the fixture to which the specimen is attached for IRT inspection had already previously heated due to the preceding thermographic analysis. Therefore, the subsequently tested sample began to heat up immediately it was attached to the test fixture, therefore somewhat before starting counting the time to capture the thermograms, when the lamp was turned on. This fully agrees with the unquestionable indication of the color pattern in Figure 7g (see reference bar of color-temperature relationship besides the thermograms) that the testpiece was warmer than in Figure 7h. An identical conclusion applies to Figures 9g and 9h, respectively, for the 16 s test.

However, it should be emphasized that this fact does not alter at all the interpretation of the results, insofar as the thermographic analyses do not depend *per se* on the absolute temperatures at different regions of the inspected part, but rather on their relative temperatures, in other words, it relies on the temperature gradients between those regions.

One can also note that the color distribution pattern (or, correspondingly, the temperature profile) on Figures 7-10 is concentric with respect to the center of the rectangular surface plates. This was cause by their heterogeneous heating during the experiment. *A priori*, it was thought that due to the punctual nature of the heating source (lamp), the center of the plate, which was closer to the filament lamp than its borders, would heat up (by radiation) faster than the edges, thus producing a pattern of colors (i.e., temperatures) warmer in the center and cooler at the edges, opposite therefore to that obtained in practice. However, it was found that the heat transfer mechanism by conduction through the box walls prevailed over that of radiation. Thus, the specimen edges attached to the box walls, which extended orthogonally to its surface (see Figure 4a) heat up faster than the specimen center, transferring energy by conduction to the edges of the laminate plate much more effectively than radiation was able to do in regard to the center of the thermo-imaged plate.

In fact, this distribution of temperatures initially raised some doubt with respect to the cold spot formed in the center of the thermograms, as if it was really created by the impact damage at the center of the plate, or it (cold spot) could only be an artifact created by the heating lamp system. However, during the thermographic survey it was in fact confirmed that the central cold spots, clearly observed for 30-Joules impact energy in both classes of laminates, corresponded precisely to the contact point between the impactor and the front face of the specimens. In addition, one can argue that if the effect was artificially created, all plates, damaged or pristine ones, would exhibit a well established cold spot as a result of the aforementioned heterogeneous heating of the impacted testpieces. However, the cold spot was clearly defined only at higher intensity impacts, of order of 20 and 30 Joules, when the traveling thermal flow through the specimen thickness were really disturbed by the damaged material. Moreover, Figures 8j to 10j indicate that the cold spot is formed in a position that does not correspond exactly to the center of the plate, which corroborates some reports that some out of the center impacts occurred due to problems on attaching the sample to the adapted Charpy impact system.

On the other hand, it can be argued that the preferential heating of the specimen edges, in detriment to its center, may have cooperated to some extent in intensifying the cold spot, which according to the arguments provided above, was created mainly as a result of the impact damage.

Anyway, to clear up any doubt regarding the potential of the IRT method to detect impact damage composite laminate structures, a more homogeneous convective heating condition of the specimens was attempted through the application of a continuous hot airflow.

3.2.2 Heating by controlled airflow

Figures 11-14 illustrate the thermograms for C-EPX and C-PPS laminates warmed up by hot airflow during two periods of time (t_a) of respectively 10 and 16 s.

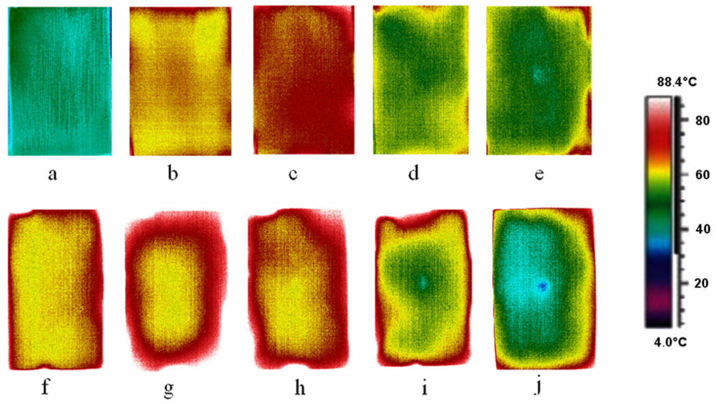

Figure 11. C-EPX thermograms by hot airjet for t_a = 10 s: (a-e) Heating approach 1; (f-j) Heating approach 2: (a, f) Impact energy = 0 Joules; (b,g) 5 J, (c,h) 10 J, (d,i) 20 J and (e,j) 30 J.

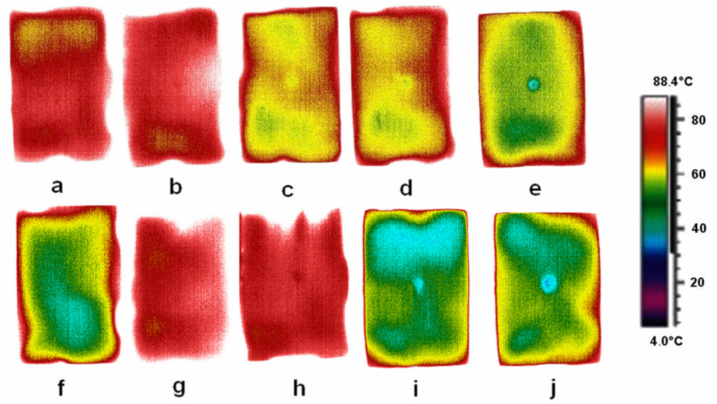

Figure 12. C-PPS thermograms by hot airjet for t_a = 10 s: (a-e) Heating approach 1; (fj) Heating approach 2: Impact energy = (a, f) 0 Joules; (b, g) 5 J, (c, h) 10 J, (d, i) 20 J and (e, j) 30 J.

The figures above display, with some exceptions, a radial (rectangular concentric) pattern distribution of colors (temperatures) in the inspected laminates, revealing again the heat transfer effect from the box walls to the laminate borders, via thermal conduction mechanism which operates concurrently to the most desirable convective mechanism. However, this pattern appears less complex, or less assorted (and no more circular) when compared to that produced by the heating lamp, indicating greater heating uniformity provided by the hot airflow method.

The thermograms in Figure 11 indicate that the impinged damage to the C-EPX specimens can only be detected by IRT from impact energies of 30 Joules, if heating approach 1 is applied for 10 seconds. However, if heating approach 2 is employed, impacts energies of 20 Joules can already be identified.

According to Figure 12, corresponding to the C-PPS laminate heated for 10 s, although the 30 Joules damage is clearly visible, 10 Joules (in heating approach 2) or even 5 Joules (heating approach 1) impact damages are prone to be identified.

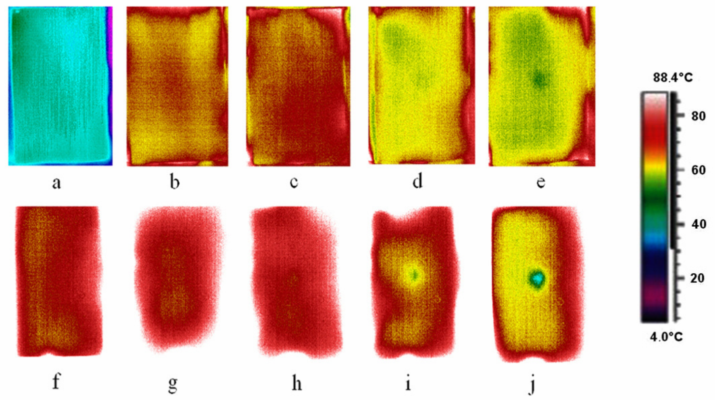

Figure 13. C-EPX thermograms by hot airjet for t_a = 16 s: (a-e) Heating approach; T (f-j) Heating approach 2: (a, f) Impact energy = 0 Joules; (b,g) 5 J, (c,h) 10 J, (d,i) 20 J and (e,j) 30 J.

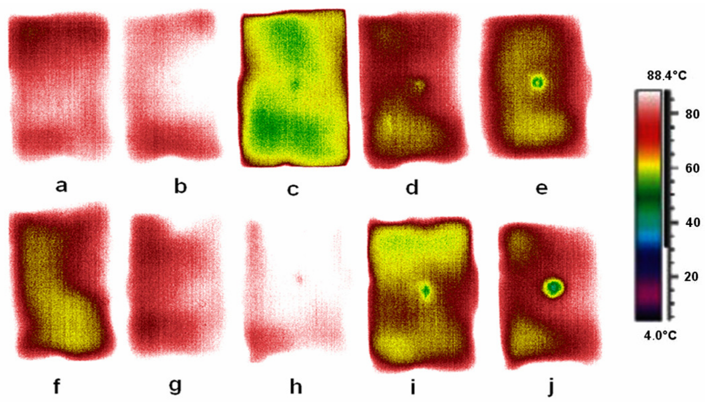

Figure 14. C-PPS thermograms by hot airjet for t_a = 16 s: (a-e) Heating approach 1; (fj) Heating approach 2: Impact energy = (a, f) 0 Joules; (b, g) 5 J, (c, h) 10 J, (d, i) 20 J and (e, j) 30 J.

The comparison of thermograms of C-EPX laminates heated for 16 seconds in Figure 13, with those presented in Figure 11 for the same material but heated for a little shorter period of 10 s, indicates a slight improvement of IRT technique to discover impact damages for longer heating times.

Analogous conclusion is drawn for C-PPS laminates by comparing their thermograms in, respectively, Figures 14 and 12.

Unlike radiation heating, where heating approaches 1 and 2 resulted in very similar thermograms, controlled hot airflow provides significantly better thermographic results when the impacted surface of the specimen faces the heating source (approach 2) as compared to approach 1.

Finally, Figure 15 shows some unpublished results regarding the application of IRT in the detection of multiple impact damage in solid PMC laminates similar to those herein assessed. The thermograms illustrate the huge potential of IRT in precisely detecting impact damage as slight as 5 J impinged to different, but close positions of the laminate plate, and not only from centralized impacts as evaluated in this work. Furthermore, the image provides in Figure 15 also show the ability of IRT technique to also detect defects and damages during the specimen's cooling cycle.

4. CONCLUSIONS

The main conclusions that can be drawn from this study on thermographic inspection of impacted PMC laminates are as follows:

1. Clearer and better defined thermographic indications of impact damage on PPS thermoplastic composite laminates were obtained as compared to identically impacted epoxy thermosetting laminates;
2. Convective heating of the impacted testpieces by controlled hot airflow was proven more efficient and convenient than by radiation using visible light;
3. Longer heating times of the inspected part favored the impact damage imaging by infrared thermography;
4. No clear trend was obtained with respect to the possible effects of the position of the impacted specimen surface in regard to the infrared camera and the heating source;

5. To some extent, impact damage detection at the center of the composite laminates was favored by the temperature profile typically developed in the test setups used for thermographic inspection, although the efficacy of the technique was unquestionably in detecting non-centralized damages as light as 5 Joules.
6. The high efficiency of the thermographic methodology to detect impact damage in high performance solid composite laminates during heat ups cycles was also reproduced along cooling down cycles.

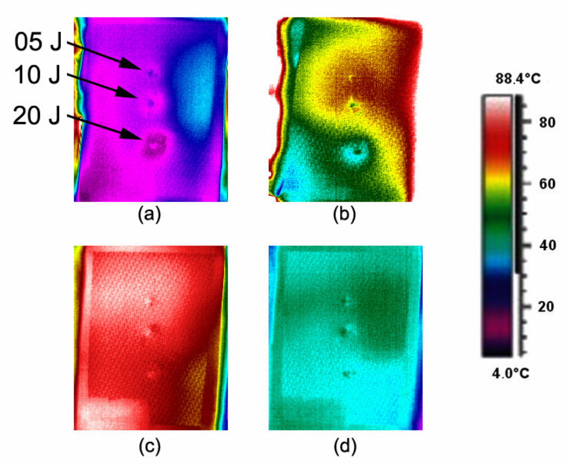

Figure 15. Transmission thermograms for a C-PPS laminate subjected to three impact loads: (a) Heating up cycle by hot airflow according to approach 1 for t_a = 12 s; (b) For t_a = 15 sec; (c) Cooling down cycle by cold airflow in accordance to approach 1 for 180 s; (d) For 345 s. The applied impact energy levels are identified by arrows.

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