Investigation of Impact Damage in Composites with Infrared Thermography

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Abstract
This work is concerned with low-velocity impact of composite materials which are mainly used for aerospace applications. Infrared thermography is used with a twofold function of surface temperature mapping when the specimen is being impacted and of non-destructive evaluation (NDE) technique. Several specimens were fabricated involving a polymeric matrix reinforced with carbon, or glass fibres and a fibre metal laminate (hybrid composite such as Glare®). Specimens were first non-destructively inspected with lock-in thermography to search for manufacturing defects, then impacted each at a different energy and again inspected with lock-in thermography. Impact tests were carried out with a modified Charpy pendulum including an impactor of hemispherical nose 24 mm in diameter. The impact energy was varied in the range 2-19 Joule by varying the height of the Charpy arm. The SC6000 infrared camera was used to view the specimen surface opposite to impact; thermal images were acquired at 96 Hz. The obtained results show that the impact on-line monitoring supplies useful information for the material characterization. In particular, the analysis of the hot zones provides understanding of the damage origin and propagation.

Keywords: Infrared thermography, low velocity impact, composites, thermal effects.

1. Introduction

Composite materials are being used ever more increasingly in the fabrication of aircraft; e.g., the big Airbus A380 is made of composites by the 25% of its structure, while an ever greater percentage is used in the Boeing Dreamliner. The main reason for this lies in the high specific stiffness and strength, combined with a significant reduction in weight, offered by such materials [1-3]. However, due to their low interlaminar strength, composites are susceptible to delamination, often resulting in considerable loss in strength, and possibly leading also to catastrophic in-service failures. Delamination is frequently caused by objects impacting the material surface and this may arise during manufacturing, service and maintenance. Within this context, mostly dangerous is the impact at low energy, that does not produce visible damage on the surface but buried delamination between the layers, which is often very slight and difficult to be detected.

Thus, it is very important, on one side, to understand the material behaviour under impact for design purposes and, on the other side, to have a tool capable to detect the damage at an early stage, before major failures or collapse occur. To these aims, a valuable technique is infrared thermography (IRT) [4-7]. IRT is a non-contact, non-intrusive technique which detects the thermal energy radiated from objects (above absolute zero) in the infrared band of the electromagnetic spectrum; such energy is then transformed into a temperature map. Indeed, a remote imaging system can be used to monitor the entire life of a product, from
manufacturing processes to final disposal, as well as during its service. In the present work, IRT is used with the twofold function of surface temperature mapping when the specimen is being impacted and of non destructive evaluation (NDE) technique to find out presence of any buried anomaly in the material. Within the impact topic, the use of IRT was recently investigated by Meola et al. [8-10] who proved that high frequency sampling rate (up to 900 Hz) makes possible to appraise the thermal effects which take place in a small time fraction. In particular, Meola and Carlomagno [10], through post-processing of thermal images and heat transfer considerations, supplied information on onset and propagation of impact damage in glass fibre reinforced polymer. More specifically, they succeeded in finding a relationship between the damaged area and the impact energy owing to the effective striking surface. Continuing the investigation of low-energy impact from the thermal point of view, the attention of the present work will be mainly focused on the location and evolution of hot spots with respect to the type of material and specifically on the fibres orientation. To pursue this goal, a high performance infrared camera is used, with sampling rate at the lower frequency of 96 Hz (with respect to previous tests), which allows viewing a larger area around the impact for a better discrimination of fibres and hot spots.

2. Experimental analysis

Experimental work was carried out on laboratory coupons by varying the material and the impact energy.

2.1 Specimen description and test setup

Several specimens were prepared of three different types of composites:

- Glass fibre reinforced polymer (GFRP) obtained from unidirectional E-glass fibres embedded in epoxy resin. The stacking sequence \( [0_2/90_2]_3 \) allowed obtaining a thickness of 2.90 mm. Laminates, 500x500 mm\(^2\), were fabricated by the hand lay-up technology and cured, under stamp, for 24 hours at room temperature. After that, rectangular specimens 130x100 mm\(^2\) were cut and post cured in oven at 60°C for 5 hours. Such specimens are named GFRP-#.

- Carbon fibre reinforced polymer (CFRP) obtained from unidirectional carbon fibres embedded in epoxy resin, of stacking sequence \( [45°/0°/-45°/90°]_3S \), were again fabricated by the hand lay-up technology but cured in autoclave. Specimens are 130x100 mm\(^2\) and 2.4 mm thick. Such specimens are named CFRP-#.

- Fibre metal laminate specimens include 3 aluminium layers with two glass/epoxy layers in between them (\( [\text{Al}]_3/[[\text{GFRP}]_2] \)) and are 130x100 mm\(^2\) and 1.5 mm thick. Such specimens are named FML-#.

Specimens were first non-destructively inspected with lock-in thermography to search for manufacturing defects. Then, each specimen was impacted on one side at a fixed energy value and monitored from the other side by the infrared camera. Each impacted specimen was again inspected with lock-in thermography. Impact tests were carried out with a modified Charpy pendulum of hemispherical shaped impactor 24 mm in diameter. Specimens were clamped from the shorter sides, while were free to move along the two longer sides. The impact energy was varied in the range 2-19 Joule by varying the height of the Charpy arm. Fig.1 shows the Charpy pendulum with the infrared camera positioned to view the specimen surface opposite to impact. The used infrared camera is the SC6000 (Flir systems), which is equipped with a QWIP detector, working in the 8-9 µm infrared band, of spatial resolution 640x512 pixels full frame and with a windowing option.
linked to frequency frame rate and temperature range. The same camera, equipped with the Lockin option, and the IRLockIn© software was used for non-destructive tests.

![Test setup for impact tests with the Charpy pendulum](image)

**Fig. 1 Test setup for impact tests with the Charpy pendulum**

2.2 Impact tests and data analysis

Sequences of thermal images were acquired at 96 Hz during impact tests. More specifically, the acquisition started few seconds before the impact and lasted for some time after to allow complete visualization of thermal effects evolution with respect to the ambient temperature. To better account for the material thermal behaviour, the first image \((t = 0)\) of the sequence, i.e. the specimen surface (ambient) temperature before impact, is subtracted to each subsequent image so as to generate a map of temperature differences \(\Delta T\):

\[
\Delta T = T(i,j,t) - T(i,j,0)
\]

\(i\) and \(j\) representing lines and columns of the surface temperature map. Therefore, a sequence of \(\Delta T\) images is created.

\(\Delta T\) images, at three time instants from the impact, for the specimen GFRP-6, which was impacted at \(E = 9.7\) J are shown in Fig.2; while images for the specimen GFRP-29, impacted at the energy of 12 J, are shown in Fig.3. The main difference between the two specimens regards the fibres orientation on the side viewed by the infrared camera, which is vertical for the GFRP-6 and horizontal for the GFRP-29 as it is also clearly explicable from thermal images.

Figs. 4 and 5 show thermal effects at three time instants respectively for the specimen CFRP-1 impacted at 2.8 J and for the specimen FML-5 impacted at 4.5 J. As can be seen, fibre reinforced polymer composites display some hot spots, which are aligned along the fibres direction. The FML-5 specimen instead displays a hot circular shaped zone; on the other side, the external layer of the FML is aluminium and then it behaves like metals to impact with also visible manifestation (i.e., bump/bowl depending on the viewed side).
During impact, kinetic energy passes from the impactor nose to the target; then, it is in part transformed into elastic energy and in part dissipated through failures, vibrations, or friction. Since most of the dissipated energy is converted into heat, the detection of the heat generation loci is important for the comprehension of failure modes; to this extent, the use of infrared thermography is essential.
From a comparison between the images acquired now at 96 Hz with the camera SC6000, and those of previous works [8-10], which were acquired at 300 and 900 Hz with the camera SC3000, the following considerations arise. First, it has to be noted that the thermoelastic effect, which evolves very fast, is now not adequately accounted for since some time shots are lost. Conversely, a wider area around the impact is now visualized, which offers the possibility for a detailed analysis of generation and development of all the hot spots. In particular, a plot of the time evolution of hot spots, which were generated under the 12 J impact on the GFRP-5 specimen, is shown in Fig.6 (for location of spots, see the image upside). In this case, there is formation of 6 spots, three of which appear soon with an abrupt temperature peak of about 30 K above the room temperature; then, in fractions of a second, decrease to 7 K while other much milder hot spots appear along the fibres direction. Of course, as recently reported by Meola and Carlomagno [10], the reached temperature value may indicate local breakage and/or delamination.

![Fig.6 Evolution of hot spots with time for the GFRP-5 specimen, E=12 J.](image)

The hot spots represent thermal perception of any form of damage arose in the material and then, information on their location, with respect to the impactor centre, is important to assess the extension of the impact damage. Thus, coordinates of each hot spots, for many specimens, were computed and represented on a $x,y$ diagram in Fig.7. The origin of axes $C(0,0)$ was assumed to coincide with the centre of the surface viewed by the infrared camera. The circumference of the impactor nose, (12 mm in diameter, which effectively struck the specimen surface) was also traced in blue with centre in $C$, with the presumption of a perfect alignment; indeed, some efforts were made, during the test setup, to align the hammer axis with the axis of the infrared detector field of view. Almost all points fall inside the blue...
hammer circumference even if the centre of the points cloud seems shifted 2 mm downside and 1 mm on the right. This is most probably due to a misalignment, and then, the circle describing the effective hammer nose should be the red one, which has centre $C'(1,-2)$ with respect to $C$. However, other factors may drive the generation of hot spots; this will be ascertained through new tests.

Fig.7 Location of hot spots within the surface effectively struck by the impactor.

2.3 Non destructive evaluation

As already mentioned, each specimen was non-destructively inspected before and after impact with lock-in thermography, thermal stimulation being performed with an halogen lamp. Several tests were carried out by varying the stimulation frequency $f$; to evaluate the material at different layers through the thickness according to the equation:

$$\mu = \sqrt{\frac{\alpha}{\pi f}}$$  (2)

where $\mu$ is the thermal diffusion length, and $\alpha$ is the thermal diffusivity. Results are presented in terms of phase images for which the depth $p$ corresponds to $1.8\mu$[11-13].

Two phase images, taken at 0.67 and 0.045 Hz of the specimen GFRP-6 after impact at 9.7 J are shown in Fig.8 together with a visible image of such specimen, which, being the material translucent, well displays the occurred damage. Similarly, a phase and a visible image are compared in Fig.9 for the specimen GFRP-29 impacted at 12 J. As can be seen, there is good correspondence between the damage mark detected via NDE (phase image) and the mark, which remained permanently on the specimen (visible image); such a mark also coincides with the extension of the hot zone, which evolves as due to coalescence of hot spots in thermal images.
Conclusions

The high sensitivity of the SC6000 camera allowed assessing the location of the hot spots within the fibres orientation; it seems all the hot spots lie within the radius of the hammer nose. The hot spots coincide with damage loci (fibre breakage) and the whole warm zone coincides with the permanent damage occurred in the material. Through observation of the formation of hot spots (one, or more), the delay between them (in case of many) and the successive enlargement of the warmed zone (coalescence of spots in case of many) it is possible to draw the map of the damage in plane and in depth. In particular, there is general agreement between the damage visualized as warm area during impact, the damage detected through non destructive inspection with lock-in thermography and the damage which remains as permanent visible mark in the case of a translucent material (GFRP).

As a next step, non-destructive tests will be repeated at intermediate frequencies and at increased spatial resolution by using a close up lens for a clearer vision of the damage extension in plane and through the thickness. Then, destructive tests with microscopic examination will follow for data fusion purposes in view of a better understanding of the damage mechanisms. To achieve this goal, both phase and thermal images will be a valuable means for decision making about where cutting specimens for microscopic examination.

References