Monitoring impact damaging of thermoplastic composites

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Abstract. Thermoplastic composites are becoming ever more attractive also to the aeronautical sector. The main advantage lies in the possibility to modify the interface strength of polypropylene based laminates by adjusting the composition of the matrix. Understanding these aspects is of great importance to establish a possible link between the material toughness and the matrix ingredients. The aim of the present work is to ascertain the ability of an infrared imaging device to visualize any change, in the material behaviour to low energy impact, induced by changes in the matrix composition. Attention is given to image processing algorithms; in particular, an original procedure to measure the extension of the impact-affected area is proposed.

1. Introduction

Infrared thermography (IRT) is a non-contact, non-intrusive technique which can be exploited for different applications in different fields [1]. Amongst others, IRT can be advantageously used in the material development sector with a twofold function: as non-destructive testing technique and as monitoring technique during material loading tests, to getting information useful to assist technicians in the materials design phase. To this end an infrared imaging device plays an unique role. In particular, it has been demonstrated [2] that monitoring the thermal signatures induced by impact (i.e. recording of thermographic images in time sequence) makes possible to getting information which are useful for the material performance, specifically for identifying the origin and propagation of impact damage. This approach, was mainly investigated owing to thermoset-matrix based materials [2,3].

The attention is now devised towards composite materials involving a thermoplastic matrix. This because thermoplastic composites, thanks to their higher damage tolerance and interlaminar toughness, as well as many other advantages (recyclability after life-cycle, reprocessing, faster production processes, chemical and environmental resistance, reduced moisture absorption and reduced costs) over the thermostet ones, are becoming ever more attractive also to the aeronautical sector. As well known, these materials react to the impact with a visible surface deformation, a concavity on the impacted side and a quasi-conical protrusion on the rear one. Then, the impact, even at low energy, produces a visible sign, making, at first sight, as superfluous the use of sophisticated non-destructive testing techniques. However, the main advantage of polypropylene based laminates lies in the possibility to modify their interface strength by adjusting the composition of the matrix [4].
Then, to make the most of their features, it is very important to understand the effects following a certain dosage of the matrix ingredients. Infrared thermography is herein proposed as means to help understanding the impact damage mechanisms and as such mechanisms modify as a consequence of matrix modifications in glass fibers thermoplastic composites. Particular attention is given to post-processing of thermal images with the intent to define the limit between sound and damaged materials in a reliable way. In fact, in presence of a hot stain, originated from the absorbed impact energy, the problem which may arise regards the minimum delta $T$ to be considered for outlining of the thermally affected area. Herein, a new procedure is proposed to measure the extension of the impact-affected area.

2. Experimental investigation

2.1. Description of specimens

Basically, the used material involves woven glass fibers embedded in a polypropylene matrix, but, in reality, two types of specimens are fabricated:

- One type includes a pure polypropylene (PP grade MA712 from Unipetrol – Czech Republic with MFI = 12 g/10 min) matrix. Specimens of this type are called PP.
- The other one includes again a polypropylene matrix, but modified with the addition of a 2% by weight of a compatibilizing agent (Polybond 3200, MFI 115 g/10 min, 1 wt% maleic anhydride, from Chemtura). Specimens of this type are called PC.

Regardless of the type of matrix, each specimen has square shape of side 240 mm. It includes 20 balanced glass fabric layers $0°/90°$ symmetrically arranged with respect to the middle plane of the laminate ($[(0/90)10]$ configuration), with a target thickness of 3 mm and a glass fiber content of 50% by volume (actual relative percentages of fiber and matrix evaluated according to ASTM D 3171-99). Films of either pure, or compatibilized polypropylene are prepared with the film blowing extrusion line model Teach-Line E 20 T (Collin Gmbh, Germany); the final thickness varying between 35 and 40 µm. Then composite laminates are obtained by alternating layers of polypropylene films and of glass fibre fabrics with the hand lay-up film-stacking technique and by using a compression molding machine (model P300P, Collin Gmbh, Germany) according to a pre-optimized molding cycle.

2.2. Impact tests

Impact tests are performed with a modified Charpy pendulum that allows positioning of the infrared camera to monitor the thermal effects developing on the specimen surface opposite to the impacted side [3]. Specimens are placed inside a special lodge which includes two larger plates with a window 15 cm x 7.5 cm to allow for the contact with the hammer from one side and optical view (by the infrared camera) from the other side. The hammer has hemispherical nose 12.7 mm in diameter. The impact energy is varied in the range 5-20 J by suitably adjusting the falling height of the Charpy arm. It is worth noting that each specimen is impacted four times in four different zones at the corners of a square area of side 120 mm, as depicted in figure 1.

The used infrared camera is the SC6000 (Flir systems), which is equipped with a QWIP detector, working in the 8-9 µm infrared band, NEDT < 35mK, spatial resolution 640x512 pixels full frame, with the pixel size 25 µm x 25 µm, and with a windowing option linked to frequency frame rate and temperature range. Sequences of thermal images are acquired during impact tests at 84 Hz frame rate. To allow for a complete visualization of thermal effects evolution with respect to the ambient temperature, the acquisition starts few seconds before the impact and lasts for some time after. To better analyze the material’s thermal behaviour, the first image ($t = 0$ s) of the sequence, i.e. the specimen surface temperature (ambient) before the impact, is subtracted to each subsequent image so as to generate a map of temperature difference $\Delta T$ [3,5]:

$$\Delta T(i,j,t) = T(i,j,t) - T(i,j,0)$$ (1)
i and j representing lines and columns of the surface temperature map. Some $\Delta T$ images are shown in figure 2 for varying the impact energy.

![Image of Charpy pendulum and specimen lodge](image)

**Figure 1.** Setup for impact tests

3. Analysis of results

3.1. Qualitative

Some $\Delta T$ images of both specimens (PP and PC) at different time instants for $E = 10$ J are shown in figures 2 and 3. Two main features suddenly catch eyes.

![Image of $\Delta T$ images](image)

**Figure 2.** Some $\Delta T$ images at different time instants during impact at $E = 10$ J of specimen PP.
Figure 3. Some $\Delta T$ images at different time instants during impact at $E = 10$ J of specimen PC.

The first one is linked to the evolution with time from thermo-elastic (cooling down) to thermoplastic (warming up) material behavior. It is worth noting that thermoplastic matrix composites react to the impact with visible modifications, like metals, displaying an indentation (a small concavity) on the impacted side and a protrusion on the rear one. Of course, these modifications are very small for very low impact energy, while they become ever more evident with increasing the impact energy. Then, the slight hot spot appearing for $t = 0.02$ s stands for the start of the material quasi-conical deformation. More specifically, such a hot spot indicates the tip of the conical protrusion, which has its basis in the warm area.

The second feature regards differences in the behavior of the two types of specimens PP and PC. In fact, unlike the PP, the PC type displays first, for $t = 0.01$ s, a well contoured dark (cool) area and at the end, $t = 3.571$ s, a smaller warm area. This because the presence of the compatibilizing agent in the matrix prevents large deformations in the impact zone.

3.2. Quantitative
To get information from thermography about the overall extension of the impact-affected zone, sequences of $\Delta T$ images are subjected to successive post-processing with routines specifically developed in the Matlab environment. To locate the damage, it is important to discriminate between sound and damaged areas. Bearing in mind that we are analyzing thermal images, what we can measure is the extension of the warmed up area, which also means delineating the zone interested by temperature increase induced by the dissipated impact energy. This, at first sight, may seem rather simple to do. Conversely, some problems may arise during evaluation of the extension of the warmed up zone.

Then, a temperature difference threshold $\Delta T_T$ must be introduced, to be considered as a limit in the $\Delta T$ maps to clearly identify the damaged zone; therefore, a criterion is necessary to avoid under/overestimation errors.

Herein a criterion based on statistical observations is proposed. Considering that a $\Delta T$ image, before the impact, is obtained as the difference between two images both at ambient temperature, this
difference should be zero for each pixel. However, a certain pixel temperature deviation is observed due to the IR camera random noise, so temperature differences are found. This is accounted for by acquiring a relatively large number of images (100) and generating an average reference $T_C$ image (cold image) from those taken before the impact. In the meantime, the temperature standard deviation $\sigma_i$ for each one of the pixels is computed. Then, it has been established that the threshold value for each pixel should be established as $\Delta T_{Ti} = 3\sigma_i$.

As far as the warm image (after the impact) $T_W$ is concerned, it is decided to take its average over a 50 images interval right after impact. Then, a given pixel in the average image right after impact is assumed to be cold, or warm depending on whether its $\Delta T$ value is greater or lower with respect to the $\Delta T_{Ti}$ value, resulting from the images before impact. Then, it is possible to transform the $\Delta T = T_W - T_C$ image in a binary image in which any pixel can assume values equal to either 0, or 1, i.e. whether it is cold (black), or warm (white) respectively. An example of transformation in binary image of $\Delta T$ is given in figure 4 for both specimens impacted at $E = 5 J$; in particular, the white/black color indicates presence of warm/cold pixels respectively. Of course, we are considering the entire warm area, which is composed of a central hottest zone surrounded by a lighter corona.

Figure 4. Examples of raw $\Delta T$ images contoured by the warm area perimeter for $E = 5 J$

Starting from the $\Delta T$ images of figure 4 it is possible to getting information about the material behavior under impact, or better on the material performance. It is possible to distinguish between the overall impact-affected zone (contoured area) and the most important damage from the value that assumes $\Delta T$. In other words, it is possible to classify the impact effects on the material from plastic deformation where the temperature increases sensibly above the ambient value, to reversible effects where very small $\Delta T$ values are found. At last, it is possible to measure the extension of each zone by simply counting the pixels enclosed in such a zone and considering the spatial resolution of the used instrument (camera and lens).

4. Conclusion

An infrared imaging device is used to monitor thermal effects, which develop on thermoplastic composites under low energy impact. The purpose is to try to get, from thermal signatures, more information on the impact damage mechanisms and if and how such mechanisms change in response to matrix modifications in glass fibres thermoplastic composites.

The obtained results shows that infrared thermography is capable to provide useful information on the effects of the matrix in the material behaviour under impact. In fact, specimens involving a compatibilizing agent in the matrix react to the impact with a plastic deformation which, at low impact energies, is much smaller than the deformation undergone by a pure polypropylene matrix at the same
conditions. These observations are derived directly from the raw thermal images, but of course, to gain quantitative information, a post processing of thermal images resulted compulsory.

An original procedure is proposed to quantitatively evaluate the extension of the hot stain produced by the impact. With this procedure a sequence of $\Delta T$ images is transformed into a sequence of binary images with any pixel forced to assume values equal to either 0, or 1, depending on a threshold value. Such a threshold value $\Delta T_T$, which is evaluated on a reference thermal image before the impact, is intended to account for the signal standard deviation of the used infrared camera and helps to discriminate temperature variations induced by the impact event.

Ultimately, $\Delta T_T$ can be used to discriminate between sound and damaged materials and to assess the overall impact-affected zone.

References

[1] Meola C and Carlomagno G M 2004 Recent advances in the use of infrared thermography Meas. Sci. Technol. 15 R27-R58.
[2] Meola C and Carlomagno G M 2009 Infrared thermography to impact-driven thermal effects, Applied Physics A 96 759-62.
[3] Meola C and Carlomagno G M 2010 Impact damage in GFRP: new insights with Infrared Thermography, Composites Part A 41 1839-47.
[4] Russo P, Acerno D, Simeoli G, Iannace S and Sorrentino L 2013 Flexural and impact response of woven glass fiber fabric/polypropylene composites Composites B 54 415-21.
[5] Meola C and Carlomagno G M 2014 Infrared thermography to evaluate impact damage in glass/epoxy with manufacturing defects, Int. J. Impact Eng. 67 1-11.

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