Learning More on Thermoplastic Composites with Infrared Thermography

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Abstract. Thermoplastic matrix-based composites (TC) are becoming ever more popular due to their many advantages over both thermoset matrix-based ones and metals. In fact, on one side, they are characterized by high damage tolerance and interlaminar toughness, due to the presence of the amorphous phase which can limit the crack propagation and allow larger deformations. On the other side, they show also advantages over the thermoset composites in terms of potential recyclability after life-cycle, reprocessing, faster production processes, chemical and environmental resistance and, usually, reduced manufacturing costs. In addition, TC performances can be tailored by the addition of a compatibilizing agent to the matrix, which allows to create a multitude of different materials. Of course, once a new material is created it requires characterization for its appropriate exploitation.

In this context, infrared thermography (IRT) represents a viable inspection means since it is non-contact, non-intrusive and can be used to monitor the entire existence of a product, from its manufacturing process to completion as well as in-service life.

In this work, IRT is used to investigate composite materials based on a polypropylene matrix, which may be either neat, or modified by addition of a relatively low amount of a specific compatibilizing agent, and reinforced with glass, or jute, fibres. IRT is used with a twofold function. First for non-destructive evaluation of materials to assure absence of manufacturing defects and to detect damage caused by loading. In particular, non-destructive evaluation is carried out with lock-in thermography which allows assessing the material conditions at different layers in a fast way. Second, IRT is used to visualize thermal effects induced in the material by cyclic bending, or impact.

The obtained results show that the presence of a compatibilizing agent in the matrix modifies the material thermal response to two types of load: cyclic bending, or impact. It results possible to follow the failure under impact from the initial deformation, to the appearance of cracks, or breakages. The comprehension of thermal effects may be useful to get information about the laden material behaviour in view of assessing the material performance.

Keywords: Thermoplastic composites, jute fibres, impact tests, bending tests, infrared thermography
Introduction

The use of composite materials is expanding in different industrial sectors from the production of means of transport to the manufacture of daily life tools. Depending on the final use, different types of ingredients are mixed to form a composite material. The driving force is generally lightness coupled with strength, formability, faster production processes, low costs as well. In particular today, the increasing environmental awareness is demanding for materials, which are environmentally friendly and sustainable. In this regard, a solution comes from thermoplastic composites, which can be created also from a natural compound and are well suited to be tailored to meet the needs of many.

The most common thermoplastic composite is generally made of polypropylene as matrix and glass fibres as reinforcement. Already so, this basic material offers many advantages in terms of fast production, reduced costs and recyclability, but, deviating a little from such a basic recipe, a variety of different materials can be obtained. For example, the addition of a little quantity of compatibilizing agent to the matrix is sufficient to change the interface strength [1], giving back a material of completely different characteristics. While playing with the ingredients may be simple and amusing, deciding the use for which the finished product may be suitable is a fairly tricky task. In fact, the use of a material depends on its characteristics (thermal, chemical, physical, etc.) and on its performance under load (tension, compression, bending, etc.). And then, the created materials require testing and characterization for an appropriate exploitation.

In this context, infrared thermography (IRT) represents a viable inspection means since it is non-contact, non-intrusive and can be used to monitor the entire existence of a product, from its manufacturing process to completion, as well as in-service life. It has already been demonstrated the usefulness of IRT within the investigation of thermoplastic composites [1-5]. In particular, it has been proved the capability of an infrared imaging device to visualize thermo-elastic effects developing over the material surface when subjected to tension/compression loads, as, for instance, under cyclic bending tests [2,3]. Besides, the same infrared camera can be used also to detect the damage caused by an impact event [4,5].

In this work, IRT is used to investigate composite materials based on a polypropylene matrix, which may be either neat, or modified by addition of a relatively low amount of a specific compatibilizing agent, and reinforced with glass, or jute fibres. The attention is mainly devised towards the monitoring of tests: cyclic bending, or impact, with the purpose to add information useful for understanding the two mechanisms. However, non-destructive evaluation with lock-in thermography is also performed to visualize the damage caused by impact events. Then, the investigation, illustrated in this work, is concerned with two tasks from either the material testing point of view, or the exploitation of the infrared camera. In fact, the infrared camera is used with a twofold function: means of video recording and non-destructive evaluation technique.

1. Description of Materials

Several laminates were fabricated involving: polypropylene grade (PP MA712 from Unipetrol – Czech Republic with MFI = 12 g/10 min), used as received, or modified with the addition of a relatively low percentage (2-5% by weight) of a common coupling agent, polypropylene grafted maleic anhydride (PP-g-MA Polybond 3200 MFI 115 g/10 min, 1 wt% maleic anhydride, from Chemtura). The reinforcement is made of plain weave type woven glass fabric (E-type glass fibres having density of 2.54 g/cm\(^3\)) with a specific mass of 204 g/m\(^2\), or plain weave type woven jute fabric with a specific mass of 250 g/m\(^2\) and
furnished by Deyute (Alicante, Spain). Each laminate has square shape of side 240 mm and thickness 3.0 mm, or 3.8 mm depending on the type of reinforcement. The original laminate is used as it is for impact tests, or cut into small specimens of width $W = 25$ mm and length $L = 125$ mm for cyclic bending tests. Some specimens details are collected in Table 1.

<table>
<thead>
<tr>
<th>Specimen Code</th>
<th>Matrix</th>
<th>Reinforcement</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>– PG</td>
<td>Neat PP</td>
<td>Woven glass fibres</td>
<td>– 3.0</td>
</tr>
<tr>
<td>– PG$_{C2}$</td>
<td>Modified PP (2 wt% PP-g-MA)</td>
<td>Woven glass fibres</td>
<td>– 3.0</td>
</tr>
<tr>
<td>– PJ</td>
<td>Neat PP</td>
<td>Woven jute fibres</td>
<td>– 3.8</td>
</tr>
<tr>
<td>– PJ$_{C2}$</td>
<td>Modified PP (2 wt% PP-g-MA)</td>
<td>Woven jute fibres</td>
<td>– 3.8</td>
</tr>
</tbody>
</table>

2. Monitoring of Materials under Mechanical Loading

Specimens are subjected to two testing ways: cyclic bending and impact tests, so two different test setups are considered.

2.1 Setup for Cyclic Bending Tests

The setup for cyclic bending tests is depicted in Fig. 1. As can be seen, the cantilever beam specimen is clamped on the bottom side (fixture) and free to bend under the cyclic harmonic displacement applied at the opposite end with an electro mechanical actuator through a wire and a return spring. More specifically, the specimen upper end is inserted into a clip attached to the wire which forces the specimen to bend under the wire alternate displacement. In reality, as can be seen from the picture, two specimens are clamped together on their bottom side, but only one is inserted inside the clip; the second one remains unloaded and is used, as reference, for correction of the camera and environmental noise [6,7]. Tests are carried out at a frequency $f_b = 2$ Hz and with deflection $D_F = \pm 7.5$ mm.

The used infrared camera is the SC6000 (Flir systems), which is positioned so as to see both specimens at once (from one surface). The infrared camera 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 bending, or better to allow for a complete visualization of thermal effects evolution with respect to the ambient temperature, the acquisition starts few seconds before displacement application and lasts for some time after.

![Fig. 1. Setup for cyclic bending tests](image-url)
2.2 Setup for Impact Tests

Impact tests are carried out with a modified Charpy pendulum, which allows enough room for positioning of the infrared camera to view the rear specimen surface (i.e., opposite to that struck by the hammer) [4,8]. Specimens are placed inside a special fixture which includes two large plates, each having a window 12.5 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 one. The hammer has a hemispherical shaped tip, 12.7 mm in diameter. Different values of the impact energy $E$ are chosen, depending on the type of material, in the range 2 - 8 J; the impact energy is set by suitably adjusting the falling height of the Charpy arm.

The used infrared camera is the SC6800 (Flir systems), equipped with an Indium Antimonide InSb MW detector, working in the 3-5 μm infrared band, spatial resolution 640x512 pixels, frame rate 565 Hz at full frame and higher with a windowing option; during impact tests, images are acquired at frame rate of 960 Hz. Again, as already made for monitoring of cyclic bending tests, the acquisition starts few seconds before impact and lasts for some time after, to allow for a complete visualization of thermal effects evolution with respect to the ambient temperature.

2.3 Image Treatment and Data Analysis

The thermal images recorded during either cyclic bending, or impact, tests are post-processed by using the Flir ResearchIR software (available from the Flir systems package) and specific routines developed in the Matlab environment. As a primary step, a sequence of $\Delta T$ images is created by subtracting the temperature for unloaded conditions (ambient temperature before starting of the load) to every image of the sequence recorded during each test. More specifically, $\Delta T$ is obtained from the relationship [8]:

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

$i$ and $j$ representing lines and columns of the surface temperature array and $t$ being the time instant at which each image is recorded.

2.3.1 $\Delta T$ Images from Impact Tests

Some $\Delta T$ images, extracted from the $\Delta T$ sequences, created according to Eq.(1), are shown in Fig. 2. Such images were chosen to highlight some peculiar aspects of the different materials that emerged during impact tests.

In particular, by looking at the images relative to the two specimens PG and PG$\text{C}_2$, it is possible to observe that, notwithstanding both specimens have been impacted at the same energy $E = 8$ J, they show some differences. In fact, the image of Fig. 2f (specimen PG$\text{C}_2$) appears much darker in its central part with respect to Fig. 2a taken at the same time instant after impact. This central dark stain, for the specimen PGC2, evolves in time maintaining its almost circular shape; instead, for the specimen PG, the darker stain tends to assume a cross shaped appearance with time. These differences may be ascribed to the presence of the compatibilizing agent in the PG$\text{C}_2$ specimen. In fact, the compatibilizing agent affects the interface strength between matrix and fibres [5] with the consequence that large deformations are prevented. It is worth remembering [4] that the dark tones indicate cooling down when the material is under tension. The compatibilizing agent (PG$\text{C}_2$) is also responsible of the appearance of the hot spots (Fig. 2i,j), which indicate formation of cracks. In fact, in the absence of the compatibilizing agent (PG specimen) the material is more ductile and can stretch and sag under the impactor pushing force, as depicted by the darker cross shaped structure of Fig. 2d.
A completely different behaviour is displayed by the PJ specimen. In fact, no dark zones are clearly evident in the $\Delta T$ images to account for any curvature of the material under the pushing impactor force; this effect may be justified owing to the low impact energy that is only 2 J. However, despite the low E value, a lighter central stain can be recognized, for $t = 0.0083$ s (Fig. 2m), which is caused by local dissipation of the impact energy [8]. After, a hot zigzag line appears (Fig. 2n), which, later on (Fig. 2o), propagates along different directions through the appearance of branches; this effect bears witness for the dynamics of the material damaging. To better bring out the different behaviours of the three specimens, time plots of minima and maxima $\Delta T$ values are reported in Fig. 3.

In the following, for convenience, minima and maxima $\Delta T$ values are named as: $\Delta T_{\text{Min}}$ and $\Delta T_{\text{Max}}$ respectively. First of all, contrary to expectation, before the impact ($t \leq 0$) $\Delta T \neq 0$; this is because the plots in Fig. 3 have been extracted by using the Matlab Max and Min routines and so, it is reasonable to find some pixels deviating from the average zero value. As can be seen, the trend of $\Delta T_{\text{Min}}$ in the specimen PG is practically identical to that of the specimen PG$_{C2}$ with only small noticeable differences. Instead, a completely
different $\Delta T_{\text{Min}}$ trend is observed for the specimen PJ; the difference is not so much in terms of amplitude, which can be justified by the low impact energy involved, but, above all, in terms of duration. In fact, $\Delta T_{\text{Min}}$ is characterized by a concavity of wide base and low height. Going to the $\Delta T_{\text{Max}}$ distribution, a different trend can be observed that seems independent of the $E$ value. In fact, despite the same $E = 8$ J for both PG and PG$_{C2}$, $\Delta T_{\text{Max}}$ of PG$_{C2}$ starts to rise early and reaches a higher value. This effect, as already mentioned, is to be ascribed to the presence of the compatibilizing agent. The PJ specimen, despite its lower $E = 2$ J value, displays an abrupt rise and highest value of $\Delta T_{\text{Max}}$. At last, by comparing $\Delta T_{\text{Max}}$ and $\Delta T_{\text{Min}}$ for the specimen PJ, it is easy to understand that this material breaks while it deforms under the impacter pushing force.

2.3.2 Variations of $\Delta T$ under Cyclic Bending

The research group at the University of Naples Federico II was one of the first to succeed to visualize and measure the thermo-elastic effects which are generated in a material under cyclic bending [9]. This measure, which is very difficult to perform due to the smallness of the temperature variations involved and to the influence of the instrument noise, is made possible with the introduction of a reference area [6] that allows for correction of the camera noise [7]. The work done till now [2,3,6,9] was driven by the chance to derive some material characteristics by simply monitoring the thermo-elastic effects owing to the general agreement between $\Delta T$ distribution and bending moment diagram. Data were mainly presented in terms of $\Delta T$ plots in time and/or $\Delta T$ against the specimen length with each plot being extracted in one point, or averaged over a small area [3].

In the present context, an effort is made to show easy to read maps of data. Then, the $\Delta T$ sequences, created with Eq.(1), are subjected to specific subsequent post-processing in the Matlab environment. More specifically, for each test, data are presented in terms of relief map of $\Delta T$ variations with time (frames) over the entire specimen length (x direction); in particular, $\Delta T$ data are averaged along the specimen width (y direction).

An example of relief map is shown in Fig. 4 for a PG specimen under bending at $f_b = 2$ Hz. As can be seen, the first tract, before load application, is characterized by $\Delta T \approx 0$ K (green color); then, $\Delta T$ becomes negative (blue color) as the viewed surface undergoes traction and after $\Delta T$ raises (red/yellow color) in conjunction with the surface undergoing compression, in a sinusoidal fashion which perfectly synchronizes with the cyclic bending. Of course, according to the bending moment, $\Delta T$ is higher in the upper side close to the fixture and decreases moving away from it (i.e. increasing x/L) along the specimen length. In particular, the wider appearance of the first red peak is due to the starting transient of the electro mechanical actuator.

![Fig. 4. Relief $\Delta T$ map for $f_b = 2$ Hz of a PG specimen](image)
3. Non-Destructive Evaluation with Lock-In Thermography

The test setup for lock-in thermography includes the specimen, the infrared camera and two halogen lamps (1 kW each) for thermal stimulation of the specimen [8]. In this case, the SC6000 camera is used (see section 2.1). For the purpose, the system is equipped with a Lock-in module that drives the halogen lamp to generate a sinusoidal thermal wave of selectable frequency \( f \) and the IRLock-In© software. Lock-in thermography is a well known technique and more details can be found elsewhere. Herein, for convenience, it is reported the basic relationship which links the thermal diffusion length \( \mu \) to the heating frequency \( f \) and to the mean material thermal diffusivity coefficient \( \alpha \):

\[
\mu = \sqrt{\frac{\alpha}{\pi f}}
\]  

(2)

The depth range for the amplitude image is given by \( \mu \), while the maximum depth \( p \), which can be reached for the phase image, corresponds to \( 1.8 \mu \).

Some phase images taken on the impacted specimens PG and PG\(_{C2}\) are reported in the following Figs. 5 and 6. As a general comment, each specimen includes two impacts at \( E = 8 \) and \( 12 \) J and is inspected by viewing both the side struck by the impactor and the rear one, each at a time. The label that is visible on the top left side of each image is used as reference to estimate dimensions. To facilitate data comparison, four images, taken at the same heating frequency, are shown side by side in the same figure. In particular, \( f = 0.53 \) Hz for Fig. 5 and \( f = 0.12 \) Hz for Fig. 6.

![Fig. 5. Some phase images taken at \( f = 0.53 \) Hz](image)

![Fig. 6. Some phase images taken at \( f = 0.12 \) Hz](image)

As can be seen by looking at the first two images, which refer to the specimen PG, a completely different appearance is displayed whether the specimen is viewed from the impacted side (Fig. 5a), or from the rear one (Fig. 5b). This because of the deformation experienced by the material. In fact, thermoplastic matrix composites react to the impact with visible modifications, displaying an indentation (a small concavity) on the impacted side and a protrusion on the rear one [10]. Of course, these modifications are very small for low impact energy, while they become ever more evident with increasing the impact energy. The two diskettes, which are visible in Fig. 5a and attain a better contrast as \( f \) is reduced (Fig. 6a), accounts for the indentation caused by the impactor tip. These diskettes
are well distinguishable also on the other figures such as in Fig. 6b in which they correspond to the tips of the protrusion cones, formed on the rear-to-impact side. The vertical rays of Fig. 5a account for the local material wrapping under the impactor pushing force; these rays appear vertically stretched because of the non uniform distribution of clamping force (rectangular window). No rays are displayed by the PG\textsubscript{C2} specimen (Figs. 5c and 6c) because, due to the stronger interfacial strength induced by the compatibilizing agent, it cannot tolerate large deformations.

4. Concluding Remarks

Some examples of application of infrared thermography to the investigation of thermoplastic composite materials have been illustrated. The obtained results show that:

- Through on-line monitoring of the thermal signatures, developing under impact tests, it is possible to get information useful for understanding the performance of materials. In particular, a small percentage of compatibilizing agent is able to prevent the material deformations at the expenses of local breakage.
- It is possible, through correction by the reference area method, to measure the small temperature variations associated with cyclic bending loading. In particular, the $\Delta T$ amplitude, being strongly dependent on the material properties, can be used as parameter in view of the characterization of newly developed materials.
- Lock-in thermography is an effective technique of non-destructive evaluation since it is capable not only to discover buried impact damage, but also to reconstruct its propagation through the material thickness. In addition, the phase images compared to the thermal images, taken during an impact event, supply information very useful for the comprehension of the impact dynamics and of the material resistance.

References