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Infrared thermography to evaluate impact damage in glass/epoxy with manufacturing defects

Carosena Meola*, Giovanni M. Carlomagno

Department of Industrial Engineering – Aerospace Division, University of Naples Federico II, Via Claudio 21, 80125 Napoli, Italy

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ABSTRACT

The capability of an infrared imaging device to visualize the thermal effects, which develop in composites under low energy impact, was recently demonstrated by Meola and Carlomagno. The current aim is now to go on in the investigation of the behaviour of a glass fibre reinforced polymer under low energy impact with particular attention to the influence of fibres orientation and manufacturing defects. Several specimens are fabricated by the hand-layup technique and cured at ambient conditions to enable formation of porosity. Such specimens are impacted with a Charpy pendulum, which allows enough room for positioning of the infrared camera to see the specimen surface opposite to the impact and to record onset and evolution of thermal signatures. The material conditions before and after impact are non-destructively checked with lockin thermography. As a main finding, manufacturing defects, like porosity and fibres misalignment, seem to play a key role in the generation and evolution of thermal signatures, which bear witness for initiation and propagation of impact damage. The obtained results show how the use of an infrared imaging device may be useful in understanding impact damaging mechanisms and establishing the delamination threshold load.

1. Introduction

Glass fibres are extensively used as reinforce in the production of composite materials meant for different types of industrial applications [1]. Of relevance is their use in the transport industry like automotive, naval and aerospace; in fact, they are used for the construction of car bodies, boat hulls and many aircraft parts as well. Moreover, glass fibres reinforced polymers are encountered also in electrical and electronic devices, in roofing panels, and in many components we normally use in everyday-life. Glass fibres are competitive because they are lightweight but cheaper with respect to other reinforcements like carbon fibres; in addition, in conjunction with aluminium, they are used for the manufacturing of Glare© [2], which it is known to have superior characteristics amongst composite materials.

However, a main weakness of all simple monolithic composites is their low interlaminar strength; in fact, they are susceptible to delamination, which is frequently caused by objects impacting the material surface, and this may occur during manufacturing, service and maintenance [3]. Mostly dangerous is the impact at low energy, which does not produce damage visible on the external surface but, rather buried delamination between the layers. In general, composites are able to absorb the impact energy within their polymeric matrix that distributes the energy in the material; in this way, a low-energy (low-velocity) impact does not produce perforation but delamination between the layers, with no visible surface manifestation, whereas the structural integrity may be severely affected [3].

Another problem within composites is linked to defects that can be accidentally induced during their manufacturing processes. Indeed, due to the numerous parameters involved, the manufacturing processes are probably the primary responsible for defects occurrence, particularly for porosity formation. In fact, porosity typically forms during an incorrect curing process due to uncontrolled, or unexpected, variations of the involved parameters, such as temperature, pressure, duration, etc. A certain percentage of gas may remain entrapped within the material (essentially the matrix) and may give rise to formation of voids, which may modify the material performance in service. In fact, it is well recognized the detrimental effects of voids on the composites mechanical properties [4,5]. Of course, the presence of porosity may affect also the behaviour of the material under impact load, with amplification of the bulk material weakness.

For the structure safe life, it is important to have availability of non-destructive testing (NDT) techniques, which are able to detect delamination at an incipient stage, as well any other buried defect. It is likewise important to know the material behaviour under

* Corresponding author. Tel.: +39 0817683621.
E-mail address: carmeola@unina.it (C. Meola).

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impact for design preventative purposes. Since the introduction of composites in the construction of aircraft, a primary task was to establish the delamination threshold load (DTL) [6]. However, notwithstanding the huge amount of available data coming from both numerical simulation and experimental testing, a methodology to unambiguously establish the DTL it is still not completely achieved. This because the DTL depends on many factors in primis the material mechanical characteristics, but also the geometry of the target [7,8] and of the impactor [9].

It is well known the high variability in mechanical properties of composites as a main consequence of porosity which is induced by manufacturing processes and which is practically unavoidable [10]; in fact the voids content can be reduced but not completely eliminated. Perhaps is this the main reason why composite materials display a large variety of damaging ways under impact [11].

In the aircraft industry there is the habit to quantify impact threats in terms of impact energy, but this, as observed by Olsson et al. [12], is not at all correct since a small mass and a large mass impactor entails, at the same impact energy, a completely different response. A solution to this drawback was recently found by Meola and Carlomagno [13] who proposed a relationship, which links the damaged area to the impact energy and to the surface area in contact with the impactor. This important result was achieved by Meola and Carlomagno while using infrared thermography to investigate the response of composites to impact events [13,14]. They proved that, with an infrared imaging device, it is possible to visualize the thermal effects, which develop under low energy impact, and which may supply information about initiation and propagation of the impact damage.

By considering that, during an impact event, kinetic energy passes from the impactor nose to the target and that such an energy is in part dissipated as heat, the detection of the heat generation loci is important for the comprehension of failure modes. In fact, any form of damage (delamination and/or fibres breakage) is accompanied by heat dissipation, which manifests itself through the appearance of hot spots/areas over the material surface. In this regard, the use of infrared thermography has to be considered as beneficial and unique.

The aim of the present work is to go on in the investigation of the behaviour of a glass fibre reinforced polymer under low energy impact with particular attention to the influence of the fibres orientation and of buried defects, like porosity and/or other manufacturing defects. The final intention is to achieve new understandings for a full validation of infrared thermography to be used to find the DTL of composite materials.

2. Experimental tests

The investigation is carried out in three steps: firstly, the material is non-destructively evaluated with optical lockin thermography (OLT) to ascertain if there is presence of manufacturing defects like porosity, slag inclusions and fibres displacement. Then, each specimen is subjected to impact tests with a modified Charpy pendulum while its rear (to impact) surface is being monitored with an infrared imaging device to visualize impact-induced thermal signatures. Finally, each impacted specimen is again non-destructively evaluated with lockin thermography to detect the damage produced by the impact.

For convenience, in the following, we first present and discuss (Section 2.2) the results obtained through online monitoring of impact-induced thermal signatures and after (Section 2.3) we compare and discuss the results obtained through non-destructive evaluation of specimens owing to both pre and post impact conditions.

2.1. Materials, instrumentation and test procedure

Several specimens, 10 cm wide and 13 cm long, are cut from 30 cm × 30 cm E-glass/epoxy laminates of stacking sequence $[0_2,90_2]_s$, fabricated by the hand lay-up technology and cured under press at ambient temperature; the overall thickness is 2.9 mm. Of course, the used curing procedure allowed formation of a certain percentage of porosity within the inner material structure. The main peculiarity of this GFRP material is to be translucent allowing visibility, to the naked eye, of imperfections for a direct comparison with results supplied by infrared thermography.

Tests are carried out using the ThermaCam SC6000 (Flir systems) which is a Stirling cooled focal plane array camera, equipped with a QWIP detector, working in the far 8–9 μm band and of spatial resolution 640 × 512 pixels full frame. In particular, two different setups are used respectively for either non-destructive testing with OLT, or impact tests with the Charpy pendulum.

2.1.1. Description of setup and procedure for OLT tests

The setup, which is sketched in Fig. 1, basically includes the specimen, the infrared camera and a halogen lamp for thermal stimulation of the specimen. More specifically, the infrared camera is equipped with a lockin module that drives the halogen lamp to generate a thermal wave of selectable frequency f. In the basic OLT, both camera and lamp are positioned on the same side to perform measurements in reflection mode. The thermal wave, delivered to the specimen surface, propagates inside the material and gets reflected when it reaches parts where the heat propagation parameters change (in-homogeneities). The reflected wave interferes with the surface wave producing an oscillating interference pattern, which can be measured in terms of temperature amplitude or phase angle ϕ, and represented, respectively, as amplitude, or phase, images. The basic link of the thermal diffusion length μ to the heating frequency f and to the material thermal diffusivity coefficient α is via the relationship:

$$\mu = \sqrt{\frac{\alpha}{\pi f}} \tag{1}$$

The depth range for the amplitude image is given by μ, while the maximum depth p, which can be reached for the phase image, corresponds to 1.8μ [15–17]. In general, it is preferable to reduce data in terms of phase image because of its insensitivity to both

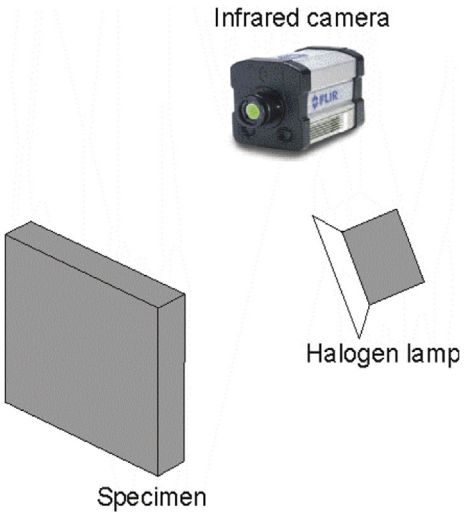

Fig. 1. Setup for non-destructive tests with lockin thermography.