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Effects of interface strength gradation on impact damage mechanisms in polypropylene/woven glass fabric composites

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ABSTRACT

The attention of the present work is focused on the behaviour of interlaminar graded interface strength (IGIS) laminated structures under impact. IGIS structures are made of layers of a woven glass fabric alternated with compatibilized and not compatibilized polypropylene film layers, symmetrically and asymmetrically arranged with respect to the middle plane. For each configuration some specimens are subjected to impact tests at energies of 6 and 25 J while one specimen is left unloaded. Impacted and not impacted specimens are non-destructively evaluated with lock-in thermography (LT). Results highlight the role played by the stacking sequence in the IGIS laminate and confirm data previously obtained through mechanical characterization.

1. Introduction

In the last decades, the ever increasing demand for lightweight structures, coupled with the intrinsic advantages of thermoplastic polymers with respect to the thermosetting ones, have been the main driving forces of some academic and industrial R&D activities. The investigation has been and is still now devised towards reinforced thermoplastic composites and their potential applications in large volume markets such as construction [1] and transportation areas [2,3].

Thermoplastic polymer composites (TPCs) offer many advantages with respect to the thermosetting ones including: fast processability and unlimited shelf life of raw materials, high damage tolerance [4] and toughness, high energy absorption capability, chemical-environmental resistance, recycling repairing and welding possibilities [5]. TPCs, initially limited to components for secondary structures, are today ever more used in primary structural components, such as vehicle front end and crash structures. Nevertheless, TPCs still suffer the fact that they are used in workflows designed for thermoset composites. This leaves room for significant improvements that may foster the integration between design workflows and manufacturing processes to further enhance the performance of the composite structures.

In this frame, commodity polymers, like polypropylene (PP), can be considered the most promising thermoplastics as matrices for composites in many industrial applications because they offer a high performance/cost ratio and a large potential market. A broad literature is available about approaches to improve the damage resistance and tolerance of composite laminates based on thermosetting matrices [6–8] but, at present, there is a relevant lack of know-how on the same topic for thermoplastic systems, especially when subjected to impact. In general, the impact resistance depends on many factors such as laminate thickness [9,10], preform architecture [11,12], level of adhesion at the fibre-matrix interface [13], laminate lay-up [14,15] and so on. Different approaches have been explored to further improve the impact behaviour of TPCs, like the simultaneous inclusion of different fibres/fillers to obtain hybrid systems, but most of them are inspired to analogous techniques used for thermoset composites. Thus, new design approaches have been considered to exploit the peculiar characteristics of thermoplastics.

The attention of this research is devised towards a new class of hybrid laminates essentially concerning modifications of the matrix rather than of the reinforcement configuration. These systems,

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named IGIS (Interlaminar Graded Interphase Strength) laminated structures, were prepared by properly alternating glass woven fabrics with polypropylene films capable of different load transfer abilities [16]. In particular, PP layers, neat or compatibilized (by inclusion of 2% by weight of a maleic anhydride grafted PP), have been arranged in symmetric or asymmetric sequences, according to a well established film-staking technology, to explore the effect of changing the interface strength through the composite thickness. Sorrentino et al. [16] demonstrated that these new configurations allow to obtain items with high flexural properties, coupled with high impact resistance without affecting the reinforcement configuration nor using fibre hybridization methods. Moreover, low velocity impact tests highlighted that grading the matrix/fibres interface strength can be an effective way to retain good mechanical properties while allowing significant increases in the impact damage tolerance by maximizing the energy dissipation through different mechanisms. Furthermore, IGIS laminates showed no, or limited, damaging of fibres at the impact energies which are capable to induce failure in conventional compatibilized laminates.

Impact damage, is a very complex event involving different phenomena such as matrix cracking, interface debonding, delamination, fibre rupture and failure [17]. These phenomena often occur without any visible signs until critical conditions are reached.

Then, the availability of non-destructive evaluation techniques (NDE) is of vital importance to ascertain the soundness of a part. The attention of the present work is focused on the use of lock-in thermography to support mechanical properties reported elsewhere for IGIS structures both by highlighting the damaging modes, occurring in these composite laminates after impact events at different energies, and clarifying mechanisms responsible for the dissipation of the impact energy. Lock-in thermography (LT) has been widely used in the evaluation of composites to detect either manufacturing defects, or damage occurring under load [18]. However, the investigation till now has mainly regarded thermoset matrix based composites with little application to thermoplastic ones. In any case, to the authors knowledge, LT has not been used yet to explore the role played by the interface strength gradation on the impact damage mechanisms. Main aim of this work is to exploit the LT potential to gain new perspectives, and/or to validate what already known from conventional characterization techniques, such as static mechanical techniques.

2. Description of specimens

The used materials are those already described in a previous work [16]; herein some details are recalled to facilitate reading.

The matrix used for manufacturing of composites was a polypropylene (PP) resin supplied under the trade name MA712 by Unipetrol (Czech Republic; MFI = 12 g/10 min). A maleic anhydride grafted polypropylene (PPgMA) was used at 2.0% by weight to improve the polymer/fibres interface (Polybond 3200 from Chemtura, Philadelphia – PA, USA; MFI 115 g/10 min, 1 wt% maleic anhydride content). A plain weave type glass woven fabric (E-type glass fibres having density of 2.54 g/cm^3, functionalized by amino silane groups) with a specific mass of 204 g/m^2 was considered as reinforcement.

Films of polypropylene, neat or compatibilized with 2 wt % of PPgMA, having a thickness equal to 35–40 μm were prepared by using a film blowing extrusion line (model Teach-Line E 20 T from Collin GmbH, Ebersberg, Germany). Composite laminates were produced by using the film stacking technique and a compression moulding machine (model P300P, Collin GmbH, Ebersberg, Germany). Neat or compatibilized polypropylene film layers were alternatively stacked between 20 layers of glass woven fabrics to obtain the desired interlaminar interface strength gradation, and compression moulded according to pre-optimized temperature and pressure profiles. IGIS configurations were prepared by changing the stacking sequence of compatibilized and not compatibilized PP films as summarized, with some of their physical properties, in the following Table 1. Fabric layers were kept balanced in all laminates using a 0°/90° symmetric arrangement with respect to the middle plane of the laminate ([(0/90)10]s configuration) with nominal target thickness of 3.3 mm and glass fibre content (V_f) of 45% by volume. The actual relative content of fibres and matrix, as well as the void content, were evaluated according to the ASTM D 3171-04 standard on each tested laminate.

3. Static and low velocity impact mechanical characterization

Flexural tests were carried out by means of a three point bending configuration set according to the ASTM D 790-10 standard, using a universal testing machine (mod. 3360 from Instron Inc., Akron – OH, USA) equipped with a 5 kN load cell. Specimens from composites (100 mm long and 12.7 mm wide) were cut from compression moulded slabs and tested by applying a displacement rate of 1.38 mm/min. The span was changed in order to keep the span-to-depth ratio equal to 16:1. Flexural modulus (E_f) and flexural strength (σ_f) were evaluated from engineering stress–strain curves, and their mean values and variance were calculated from at least five specimens for each configuration. Low-velocity impact tests were performed at two impact energies (E = 6 J and E = 25 J) by means of an instrumented drop-weight impact testing machine (model Fractovis Plus from CEAST, Pianezza (TO), Italy) equipped with a hemispherical tip (diameter 12.7 mm). The impact velocity was kept constant and equal to 2.5 m/s. The sample holder was a stainless steel annular ring (internal diameter 40 mm, outer diameter 60 mm). For each composition, a minimum of 4 samples, measuring 80 mm × 80 mm and cut from the prepared laminates, were tested and their mean values and variance were calculated. All laminates were characterized within three days after their production.

The static flexural characterization of conventional as well as IGIS laminates showed that the presence of the coupling agent had a positive effect on both flexural modulus and flexural strength (Table 2). COMP laminates clearly showed improved flexural modulus and flexural strength with respect to the NEAT ones due to the enhanced capability, in compatibilized systems, of better transferring the load between the matrix and the woven fabric

Table 1
Investigated IGIS configurations and some of their physical properties.

Sample	Polymer layers sequence	Thickness (mm)	Density (g/cm^3)	V_f (%)	Voids content (%)
NEAT	20 N	3.63 ± 0.04	1.59 ± 0.01	42.1 ± 0.5	0.8 ± 0.3
COMP	20C	3.05 ± 0.03	1.73 ± 0.01	49.9 ± 0.3	0.3 ± 0.2
HNC	10 N/10C	3.43 ± 0.03	1.63 ± 0.01	45.2 ± 0.6	0.4 ± 0.2
HCN	10C/10 N	3.12 ± 0.02	1.63 ± 0.01	45.3 ± 0.4	0.4 ± 0.2
HNCN	5 N/10C/5 N	3.14 ± 0.02	1.63 ± 0.01	47.5 ± 0.7	0.4 ± 0.2
HCNC	5C/10 N/5C	3.41 ± 0.02	1.67 ± 0.01	45.7 ± 0.4	0.5 ± 0.2
HX	2C/5 N/6C/5 N/2C	3.30 ± 0.03	1.67 ± 0.01	47.2 ± 0.5	0.6 ± 0.2