MICRO-SCALE IMPACT TEST SYSTEM FOR ASSESSING DAMAGE PROPAGATION IN CROSS-PLY THERMOPLASTIC LAMINATES

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Keywords: Impact, mechanical test, damage, thermoplastic composite

Abstract

We developed a micro-scale impact test system to observe transverse crack and delamination in cross-ply laminates under impact. The system mainly consists of custom-made 3-point bending test setup with two stiff springs, high-speed camera and force measurement instruments. We captured the propagation of transverse crack and delamination using the high-speed camera in continuous glass fiber-reinforced polypropylene laminates $[0_4/90_8]_T$ with an initial crack under the low-velocity impact of 3.2 m/s. Our objectives are: (i) to reveal the nature of damage propagation in glass/polypropylene under impact at fiber-matrix level, (ii) to study the influence of matrix ductility on damage behavior by testing glass/polypropylene of two different polypropylene matrices, homopolymer PP (GF-PP) and impact-enhanced copolymer PP (GF-IPP). We compared the results with our previous test at quasi-static. Our results show that our proposed test system is quite effective in providing an insight into damage propagation (transverse crack and its transition to delamination) of thermoplastic composites under high-speed loading. Furthermore, we found that the transverse crack propagation is unaffected by the loading speed and matrix ductility, while the delamination is very sensitive to both factors.

1. Introduction

Thermoplastic composites with continuous fibers are increasingly used to manufacture automotive components due to their good impact resistance, tailorability, fast processing, ‘infinite’ shelf life and recyclability. Glass/polypropylene is one of the thermoplastic composites that could meet above criteria with a balance between material cost and impact properties.

Measuring the impact resistance of composites typically requires a drop tower and large number of laminates. Such standard impact test system does not allow for tracking a very detailed crack propagation at fiber/matrix scale. One alternative for this is to use a micro-scale test setup that provides a clear tracking of damage propagation and, at the same time, an estimation of energy release rate. Tracking the damage propagation at micro-scale has been performed for quasi-static speed case [1-4]. An in-situ experimental setup for damage tracking at micro-scale has been reported in Ref. [5] although the damage was observed at meso-scale level.

The objectives of our research are two-fold. Firstly, we could establish a method to measure the damage propagation in glass/polypropylene under impact at fiber-matrix level. Secondly, we studied the effect of matrix ductility on damage propagation by testing glass/polypropylene of two different polypropylene matrices, namely homopolymer PP (called "GF-PP") and impact-enhanced copolymer PP (called "GF-IPP"). This paper reports the preceding work towards our paper [6].

2. Experiments

Two types of materials provided by SABIC were used in this experiment. First material was glass fiber reinforced homopolymer polypropylene (called "GF-PP"), while the second one was glass fiber reinforced impact copolymer polypropylene (called "GF-IPP"). GF-IPP contains ethylene-propylene rubber particles as an impact enhancement. As a neat matrix, homopolymer PP is stronger and stiffer than copolymer PP [7].

The stacking sequence of the laminate was $[0_4/90_8]_T$ made by adopting static press method using metallic mold under PEI 15T hot press machine. We cut the laminate into a small piece of specimen: 40 mm length, 6 mm width, 3 mm thickness. An initial crack (notch) of 1 mm in [90] plies was created using the water-cooled diamond saw. The surface of the specimen was polished at various roughnesses (grit #500 – #4000) and sputtered with 6 nm platinum/palladium (Emitech K575X).

The mechanical impact test was performed by applying an impact load on the center of [0] plies, while the sample was supported by two pins (30 mm apart) on the [90] plies. Crack would grow from the notch tip to the [0/90] interface, and delamination ensued at the interface towards two directions. This experiment was performed using our in-house test device displayed in Fig. 1 consisting of the spring-loaded system, loading pin (force acquisition rate was 500 kHz), specimen fixture, loading screw for compressing the springs, Wheatstone bridge connected to the oscilloscope. With the current spring stiffness and maximum compression, we could achieve a 3.2 m/s impact velocity, which is typically the speed for low-velocity impact.

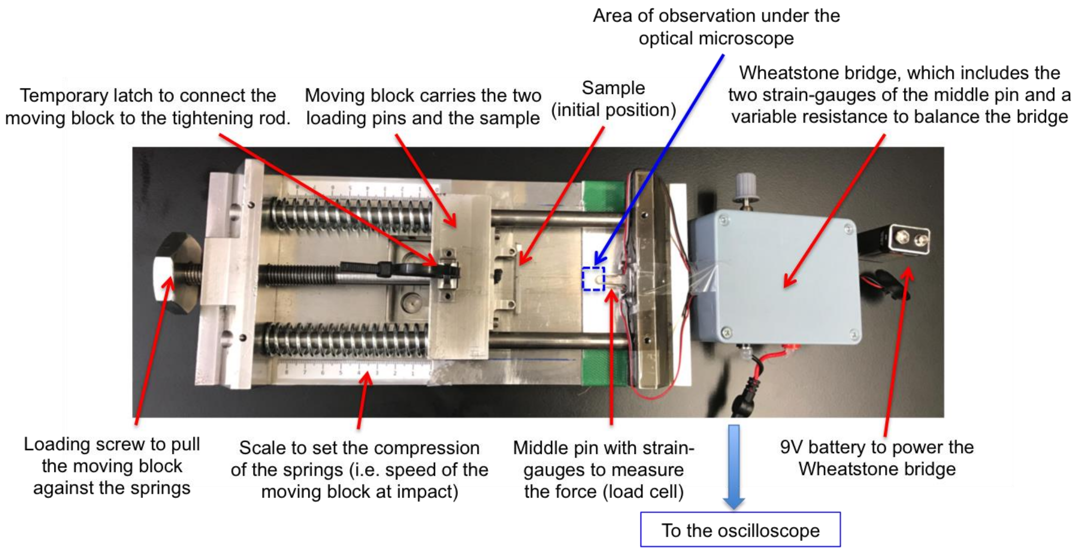

Figure 1. Micro-scale impact test device

The crack propagation was captured using the high-speed camera (Phantom v2511) that was fitted into an optical microscope (Zeiss SteREO Discovery.V20). The image acquisition frequency depends on the lens magnification: 50x magnification (8.12 μm/pixel) requires 39,000 frame/s, 180x magnification (2.26 μm/pixel) requires 62,000 frame/s. Camera exposure time was kept between 16-17 μs. The illumination of the light source did not cause a heating (temperature rise) since the impact duration occurred only 3-4 ms. The experimental setup can be seen in Fig. 2.

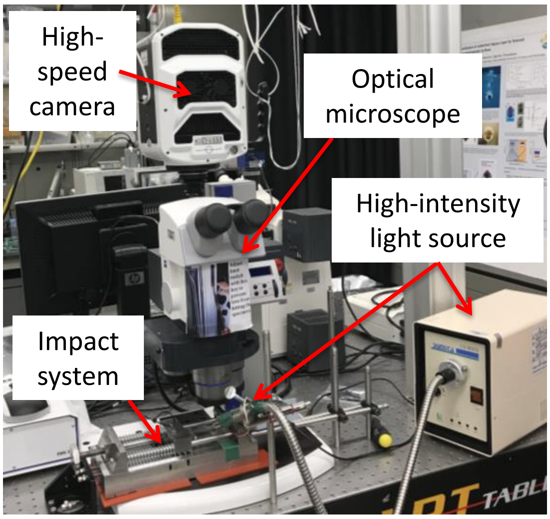

Figure 2. Experimental setup for impact micro-scale damage observation.

3. Results

3.1. Force-displacement curves

Force-displacement curves of GF-PP and GF-IPP obtained from micro-scale impact test are shown in Fig. 3. Both materials exhibit similar curves, particularly in the initial stage, which is dominated by the dominance of [0] plies and high-frequency oscillations (ringing). The ringing phenomenon is because of impactor vibration and simply-supported boundary condition. Here, GF-PP shows higher maximum force and displacement-at-failure than GF-IPP. The failure point was determined by the compressive buckling load of [0] plies under the impactor. GF-PP has higher stiffness, and thus the buckling load, in comparison with GF-IPP. We can also see from Fig. 3 that albeit small-sized specimens (which could be prone to the variability of fiber volume fraction, non-uniform thickness among samples) the tests were found to be repeatable.

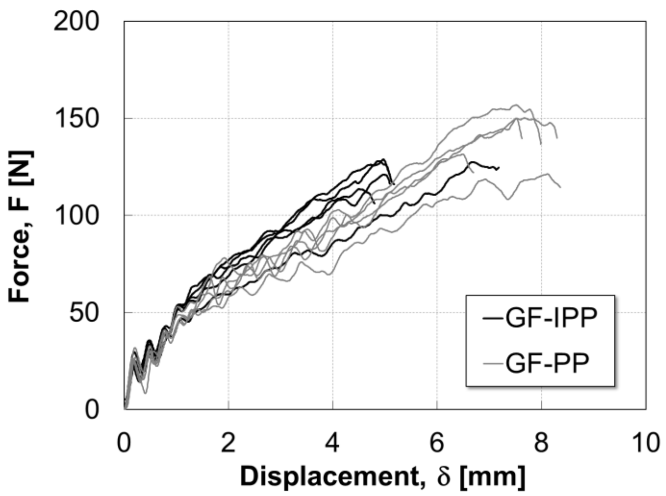

Figure 3. Force-displacement curves of GF-PP and GF-IPP under impact.

3.2. Damage propagation

Fig. 4 shows the damage propagation captured by the high-speed camera. In this regard, PP type does not pose any difference in terms of the transverse crack mode in glass/polypropylene, indicating that transverse crack at high-speed is not driven by the matrix properties. It is controlled by the interfiber distance of the ply. Fibrillation is observed in the delamination phase of GF-IPP. GF-PP does not show a fibrillation as in GF-IPP, suggesting that the nature of GF-PP's delamination is brittle. The fibrillation may have a role in delaying the growth of delamination (as a mixed-mode fracture) in GF-IPP.

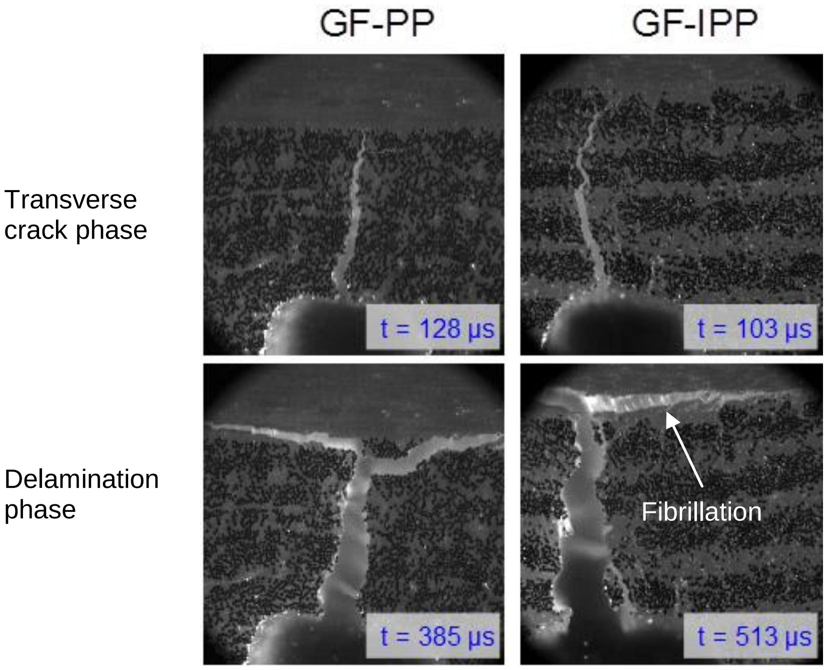

Figure 4. Damage propagation in GF-PP and GF-IPP under impact.

3.3. Calculation of energy release rate

Images obtained from micro-scale damage observation were used to estimate the crack length at every time step. Once the crack during transverse crack and delamination stages was measured, we used following expression to calculate the strain energy release rate:

$$G = -(1/2B)(\partial/\partial a)(F.\delta) \quad (1)$$

Where G is the strain energy release rate, which is to be calculated for every stage; B is the specimen width; a is the crack length; F is the force; δ is the displacement. The density of the material is considered very low, so we can neglect the effect of inertia in this case.

Table 1 shows the summary of strain energy release rate calculated from micro-scale impact tests. Here, we can see that *G* during transverse crack phase is similar for these two materials. Two materials exhibit similar growth of transverse crack despite the loading speed, i.e. quasi-static (already reported in Ref. [4]) or present impact test. As for the delamination phase, *G* is significantly different for GF-PP and GF-IPP. *G* during delamination for GF-IPP is almost double than that for GF-PP. PP with rubber particles in GF-IPP system is very effective in delaying the growth of delamination during impact.

Table 1. Strain energy release rate (*G*) calculated from micro-scale impact test results.

Material type	*G* during transverse crack (kJ/m^2)	*G* during delamination (kJ/m^2)
GF-PP	0.56 ± 0.16	2.65 ± 0.31
GF-IPP	0.62 ± 0.30	5.82 ± 1.16

3.4. Comparison with macro-scale impact test

We performed low-velocity impact test using Instron CEAST 9350 on a standard specimen (110 mm x 110 mm x 2 mm) at various impact energies (12, 18, 24, 30). We measured the lateral delamination length in cross-ply laminates $[0_2/90_2]_s$ of GF-PP and GF-IPP after the impact test [7]. We compared qualitatively the trend of damage growth obtained from micro-scale and macro-scale impact tests. In brief, we conclude that the micro-scale impact test proposed herein was able to obtain a similar trend of damage phenomenology as the one obtained from macro-scale standard impact test.

3.5. Digital image correlation (DIC) analysis

We also performed digital image correlation (DIC) analysis using fibers as a speckle pattern. The objective was to demonstrate that we could use the current images for obtaining the strain field, which could be useful to validate micromechanical modeling. Firstly, the image of fibers in front of the crack tip was processed using *ImageJ* software. Two images were needed to prepare the reference image (undeformed state) and deformed state image. Then, we used VIC 2D to determine the region of interest, strain window, subset size, and step size. We finally obtained the displacement and strain fields from this software. The examples of the strain field (ε_{yy}) in GF-PP and GF-IPP could be seen in Fig. 5. Due to a limited number of frames/images, we could not generate the time-strain curves. Nonetheless, we have demonstrated that if a sufficient number of frames during the transverse crack phase is available, a more meaningful comparison between two materials could be obtained.

4. Conclusions

We developed a micro-scale impact test system for analyzing the damage propagation at fiber/matrix scale and measuring the strain energy release rate of two different thermoplastic material systems (glass/polypropylene with homopolymer PP, glass/polypropylene with impact copolymer PP). The system proposed here is effective in capturing the damage propagation phenomena at micro-scale, which is useful in the direct evaluation of strain energy release rate. This system is able to screen two different materials based on their damage behavior. Comparison of damage phenomenology was carried out with a more standard test (low-velocity impact) using Instron CEAST 9350. The comparison of damage phenomenology shows that our system was able to capture the trend of damage quite well. Furthermore, another benefit of this system is that the sample size is relatively small, enabling cost-effective material screening based on its damage phenomenology.

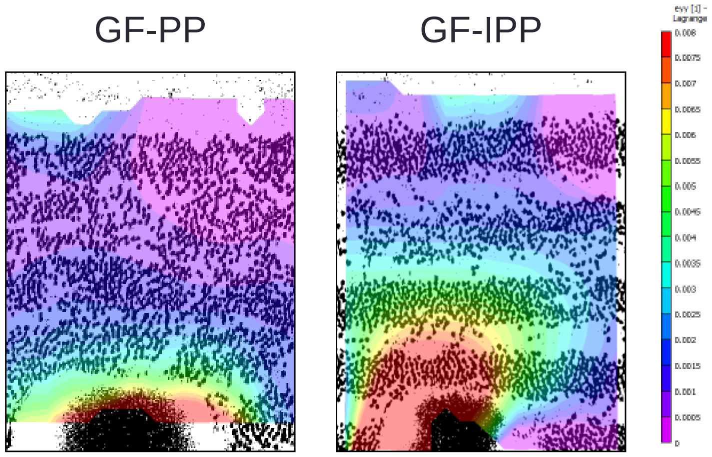

Figure 5. Strain field in front of the crack tip in GF-PP and GF-IPP under impact obtained by digital image correlation (DIC) technique

Acknowledgments

We would like to thank the Saudi Basic Industries Corporation (SABIC) for providing research fund (Grant Agreement No. RGC/1/2050-01-01), materials, and other scientific supports. This work was also partially supported by Baseline Research Funds from King Abdullah University of Science and Technology (Award No. BAS/1/1315-01-01). We also thank the research support from High-Speed Fluids Imaging Laboratory of KAUST (Prof. S. Thoroddsen, Mr. T. Alghamdi).

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