Monotonic and cyclic responses of impact polypropylene and continuous glass fiber-reinforced impact polypropylene composites at different strain rates

<table>
<thead>
<tr>
<th>Item Type</th>
<th>Article</th>
</tr>
</thead>
<tbody>
<tr>
<td>Authors</td>
<td>Yudhanto, Arief; Lubineau, Gilles; Wafai, Husam; Mulle, Matthieu; Pulungan, Ditho Ardiansyah; Yaldiz, R.; Verghese, N.</td>
</tr>
<tr>
<td>Citation</td>
<td>Monotonic and cyclic responses of impact polypropylene and continuous glass fiber-reinforced impact polypropylene composites at different strain rates 2016 Polymer Testing</td>
</tr>
<tr>
<td>Eprint version</td>
<td>Post-print</td>
</tr>
<tr>
<td>DOI</td>
<td>10.1016/j.polymertesting.2016.03.008</td>
</tr>
<tr>
<td>Publisher</td>
<td>Elsevier BV</td>
</tr>
<tr>
<td>Journal</td>
<td>Polymer Testing</td>
</tr>
<tr>
<td>Rights</td>
<td>NOTICE: this is the author’s version of a work that was accepted for publication in Polymer Testing. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in Polymer Testing, 8 March 2016. DOI: 10.1016/j.polymertesting.2016.03.008</td>
</tr>
<tr>
<td>Download date</td>
<td>2023-11-01 10:35:01</td>
</tr>
<tr>
<td>Link to Item</td>
<td><a href="http://hdl.handle.net/10754/601020">http://hdl.handle.net/10754/601020</a></td>
</tr>
</tbody>
</table>
Monotonic and cyclic responses of impact polypropylene and continuous glass fiber-reinforced impact polypropylene composites at different strain rates

A. Yudhanto, G. Lubineau, H. Wafai, M. Mulle, D.A. Pulungan, R. Yaldiz, N. Verghese

PII: S0142-9418(16)30045-9
DOI: 10.1016/j.polymertesting.2016.03.008
Reference: POTE 4603

To appear in: Polymer Testing

Received Date: 21 January 2016
Accepted Date: 7 March 2016


This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.
Material Properties

Monotonic and cyclic responses of impact polypropylene and continuous glass fiber-reinforced impact polypropylene composites at different strain rates

A. Yudhanto¹, G. Lubineau¹*, H. Wafai¹, M. Mulle¹, D. A. Pulungan¹, R. Yaldiz², N. Verghese²

¹King Abdullah University of Science and Technology (KAUST), Physical Science and Engineering Division, COHMAS Laboratory, Thuwal 23955-6900, Saudi Arabia
²SABIC T&I Corporate Research Development, Composites, P.O Box 319, 6160 AH Geleen, The Netherlands

*Corresponding author’s e-mail: gilles.lubineau@kaust.edu.sa

Abstract

Impact copolymer polypropylene (IPP), a blend of isotactic polypropylene and ethylene-propylene rubber, and its continuous glass fiber composite form (glass fiber-reinforced impact polypropylene, GFIPP) are promising materials for impact-prone automotive structures. However, basic mechanical properties and corresponding damage of IPP and GFIPP at different rates, which are of keen interest in the material development stage and numerical tool validation, have not been reported. Here, we applied monotonic and cyclic tensile loads to IPP and GFIPP at different strain rates (0.001/s, 0.01/s and 0.1/s) to study the mechanical properties, failure modes and the damage parameters. We used monotonic and cyclic tests to obtain mechanical properties and define damage parameters, respectively. We also used scanning electron microscopy (SEM) images to visualize the failure mode. We found that IPP generally exhibits brittle fracture (with relatively low failure strain of 2.69-3.74%) and viscoelastic-viscoplastic behavior. GFIPP [90]₈ is generally insensitive to
strain rate due to localized damage initiation mostly in the matrix phase leading to catastrophic transverse failure. In contrast, GFIPP [±45], is sensitive to the strain rate as indicated by the change in shear modulus, shear strength and failure mode.

Keywords: Polypropylene, glass/polypropylene, damage, strain rate

1. Introduction

Thermoplastic composites are attractive to the automotive industry because of their excellent impact performance, rapid processing time and recyclability [1]. Interest from the automotive industry in thermoplastic composites has grown even more strongly with new regulations on CO₂ emissions and increased environmental awareness over the last few years. Glass fiber-reinforced polypropylene is one of the most widely used thermoplastic composites for fabricating automotive parts. While the industry has relied on the use of short [2][3] or long discontinuous fibers [4][5], unidirectional (UD) tapes utilizing continuous glass fibers are also an emerging and promising solution. Improved mechanical performance, lighter weight, effective tailoring of laminate lay-up, ease of integration with other structural parts, increased freedom for design complexity, and rapid processing time are the main reasons for the use of continuous glass fiber polypropylene.

The key techniques to improve the mechanical performance of laminated composites are to strengthen the fiber-matrix interface, to modify the properties of the matrix and to improve fiber impregnation and dispersion. To strengthen fiber-matrix interfacial adhesion in glass fiber-reinforced polypropylene, coupling agents from the silane family (e.g., amino silane) can be used to size (coat) the glass fibers to improve their interfacial shear strength. Stronger fiber-matrix cohesion is derived from the formation of fiber-matrix covalent bonds and from the formation of an interphase network between the matrix and coupling agent [6]. The properties of the matrix can be modified by blending a toughener into the matrix to improve the ductility. For instance, ethylene-propylene rubber (EPR) can be added to isotactic homopolymer polypropylene to improve its toughness and impact resistance. The toughening mechanism is realized when the EPR particles blunt the crack and inhibit crack propagation [7]. This blended polypropylene is widely known as impact polypropylene (IPP) [7][8][9][10].
Thus far, monotonic stress-strain responses at different rates have been obtained for isotactic polypropylene (PP) [11], homopolymer PP [11], SBS-filled PP [13] and talc-filled PP [14][15]. The monotonic and cyclic responses of copolymer PP were studied by Zrida et al. [16][17] although the cyclic strain rate was limited to 0.001/s [16]. Data on the failure morphology and cyclic response of IPP up to 0.1/s have not yet been published. The evaluation of [90]s and [±45]s is important to understanding how matrix-dominated laminates based on IPP may behave. Continuous glass fiber-reinforced polypropylene was studied by Rijsdijk et al. [18] and Hamada et al. [19]. The in-plane shear response of glass/polypropylene was studied by Davies and Cantwell [20], Papadakis et al. [21][22] and Wafai et al. [23]. The in-plane shear response under various rates of thermoset composites (glass/epoxy), on the other hand, has been well researched [24]. The damage mechanism of various basic glass/polypropylene laminates was studied by performing frequency-based acoustic emission analysis [25]. Notwithstanding these prior investigations, the effect of strain rates on the overall monotonic, cyclic and failure morphology of newly developed GFIPP composites, especially in matrix-dominated lay-ups (representing transverse and in-plane shear behavior), has so far not been documented.

Here, we characterized the mechanical properties of impact polypropylene and its composite form (continuous glass fiber-reinforced impact polypropylene, GFIPP) subjected to monotonic and cyclic tensile loading at different quasi-static rates (0.001, 0.01, 0.1/s). We also studied the transverse and in-plane shear response of GFIPP by performing uniaxial tensile tests of [90]s and [±45]s, respectively. The evaluation of [90]s and [±45]s is important to understanding how matrix-dominated laminates based on IPP may behave. The obtained properties were used to feed and validate in-house micromechanical models that are able to identify the design parameters controlling damage behavior.

The remainder of this paper is organized as follows. Section 2 describes the experimental details, including materials, processing, specimen preparation and testing procedures for neat IPP and GFIPP. In Section 3, we report the monotonic and cyclic response and the failure morphology of IPP under different quasi-static rates. We also describe transverse...
and in-plane shear behavior of GFIPP under different strain rates. Section 4 concludes the paper.

2. Experimental

2.1. Materials

The material under investigation was continuous glass fiber-reinforced impact polypropylene (GFIPP) produced by SABIC. The glass fiber was E-glass, while the matrix was impact copolymer polypropylene (IPP). GFIPP composites were provided in the form of continuous tapes (110 mm wide, 0.25 mm thick). The volume fraction of the glass fiber as measured based on optical microscopy images was 46.5%. The diameter of an average fiber was 16.3 µm. The neat IPP used in our experiments was also produced by SABIC, and provided in the form of injection-molded plaques (300 mm × 80 mm, 2 mm thick). This IPP is a modified polypropylene made by SABIC in which homopolymer PP is loaded with ethylene-propylene in the rubber phase and modified with maleic anhydride. In addition, amino silane was applied to the glass fibers to improve the fiber-matrix adhesion between the E-glass fibers and polypropylene.

2.2. Processing of materials

To make GFIPP laminates, we prepared a stack of unidirectional tapes. We explored two basic lay-ups, i.e., [90]_8 and [±45]. The edges of the tapes were sealed by polyimide tapes containing adhesive silicon (Kapton® by DuPont) to avoid leakage during processing. The laminate was inserted into a custom-designed steel mold in which the internal surfaces were coated three times with a release agent (TP 920 multi-pole). Each application of the release agent was followed by an interval of 20 minutes. We used a hot press machine (Pinette Emidecau Industries 15T) to statically press the laminates in the mold with the following consolidation cycle: (i) application of 7.5 bar pressure and simultaneous increase in temperature from 30 to 210 °C, (ii) pressure maintained at 7.5 bar and temperature maintained at 210 °C for 20 minutes, (iii) hot press cooled down with a pre-set cooling rate of 40 °C/min until the temperature reached 25 °C (the pressure was maintained at 7.5 bar until this last cycle was complete). The actual cooling rate, as measured using a
thermocouple and fiber Bragg grating sensors, was 22 °C/min [26]. Neat IPP plaques were also reprocessed under the same conditions as the GFIPP laminates to ensure similar crystallinity in both the bulk polymer and composite samples. The thickness of the plaques after reprocessing was 2.01±0.05 mm, which is similar to the thickness of the as-received, injection-molded IPP plaques.

2.3. Test procedures

Quasi-static tensile tests were first carried out on neat IPP specimens. The specimen for neat IPP followed the ISO 527-2 1BA standard (dumb-bell shaped) with the following dimensions: 75 mm long, 5 mm wide and 2 mm thick. The dumb-bell specimen was made by stamping the IPP plaque with a metal die (Pioneer Dietecs). The quasi-static tensile tests (monotonic and cyclic) were conducted using an Instron 5882 test machine (500 N load cell) at loading rates of 3 mm/min, 30 mm/min and 300 mm/min, which correspond to strain rates (\( \dot{\varepsilon} \)) of 0.001/s, 0.01/s and 0.1/s, respectively (the sample free-length was 50 mm). The strains were measured using a non-contacting video extensometer (SVE2 by Instron) by tracking two contrasting dots (which were 20 mm apart in the longitudinal direction) on the IPP specimen. Parameters obtained by the Bluehill software were stress-strain curves, tensile modulus, yield stress (maximum stress) and failure strain.

Quasi-static tensile tests were conducted on \([90]_8\) and \([\pm45]_s\) specimens to obtain transverse and in-plane shear properties, respectively. The Instron 5944 test frame (2 kN load cell) was used. We referred to both ISO 527-5 and ASTM D3039 for general sample preparation and testing procedure. However, we applied certain adjustments, e.g., determination of specimen dimension, utilization of tabs and determination of loading speed, to meet our objective in exploring new development materials. Specimen dimensions for \([90]_8\) and \([\pm45]_s\) were 110 mm long and 20 mm wide. The thicknesses for \([90]_8\) and \([\pm45]_s\) were 2 mm and 1 mm, respectively. No tabs were used for GFIPP laminate. Three loading speeds were assigned: 4 mm/min, 40 mm/min and 400 mm/min, corresponding to \( \dot{\varepsilon} \) of 0.001/s, 0.01/s and 0.1/s, respectively (the sample free-length was 70 mm). The strain fields (\( \varepsilon_{xx}, \varepsilon_{yy} \)) of GFIPP were measured using a digital image correlation system (DIC). A SensiCam 12-bit CCD camera (PCO) with TC-12080 bi-telecentric lenses...
(The Telecentric Company) was used. We used CamWare V3.11 (PCO) software to capture the speckle-patterned images acquired from the CCD camera. The region of interest (ROI) for GFIPP was defined at one value between 96×64 and 864×448 pixels depending on the loading speed. Likewise, the set frame rate was between 1 to 50 frames per second (fps) depending on the loading speed (the higher the loading speed, the higher the frame rate). The speckle-patterned images acquired by CamWare were then processed using VIC-2D (Correlated Solutions). In processing these images, the subset size was determined at one value between 9×9 and 85×85 pixels (px) depending on the image quality. Likewise, the step size (distance between subsets) was set at one value between 1 and 10 pixels, also depending on the image quality. Table 1 gives the DIC parameters in the GFIPP tests. Synchronization of data between the Instron and DIC systems was manually post-processed with a spreadsheet program.

2.4. Failure observation by SEM

The failure morphology of IPP and GFIPP composites was determined using a scanning electron microscope (SEM). The IPP and GFIPP samples (which were non-conductive) were first coated (sputtered) with gold/platinum (Au/Pd) for 68 seconds (the thickness of the coating was 6 nm) using an Emitech K575X sputter coater (Quorum Technologies). This sputtering was done to improve the conductivity of the sample by reducing the charging effect from the sample’s surface. The next step involved inserting the sample into the stage inside the Quanta 600F (FEI) SEM machine. We used several magnifications ranging from 500× to 60,000× to provide sufficient detail of the fractured surface of the material.

3. Results and discussion

3.1. Response of impact polypropylene

3.1.1. Monotonic response and failure morphology

Stress-strain curves of IPP under different strain rates are shown in Fig. 1. At least three specimens were tested for each strain rate. Good repeatability was observed. Monotonic tensile properties derived from stress-strain curves are presented in Table 2. It is clear that a
higher strain rate results in higher tensile strength and failure strain. The tensile modulus, which is determined from the slope of the stress-strain curve between \( \varepsilon = 0.05\% \) and \( \varepsilon = 0.25\% \), is also affected by the strain rate. In this regard, IPP seems to exhibit viscoelastic-viscoplastic behavior.

Fig. 2 displays SEM images of fractured surfaces of IPP at different strain rates. The images show that different strain rates do not seem to change the fracture morphology. These are typically two regions in the fractured surfaces of IPP samples, a brittle fracture region and a ductile fracture region. The brittle fracture region is shown in the top row of Fig. 2, where a vast amount of dimples and humps can be seen. The dimples, which are uniformly distributed across the surface, indicate traces of ethylene-propylene rubber particles that were added to the IPP; these traces are similar to those observed in [8][9][28]. The humps are composed of rubber particles covered by the IPP matrix. The bottom row of Fig. 2 shows the ductile fracture region where microfibrils (plastically deformed crazes protruding from the fractured surface) are scattered around the humps and dimples. The area of the ductile fracture region is actually smaller than the area of the brittle fracture region, suggesting the dominance of brittle fracture in IPP at the studied strain rates.

3.1.2. Cyclic response and damage parameter

Representative stress-strain curves of neat IPP obtained from cyclic (loading/unloading) tests at different strain rates are shown in Figs. 3a-c. Each curve is characterized by 5 to 6 hysteresis loops. Consistent with the monotonic test results, IPP exhibits viscoplastic response under cyclic loading. The damage parameter or stiffness degradation, \( d \), is then derived based on these loading/unloading curves. \( d \) is defined as \( d = 1 - E_i/E_0 \), where \( E_0 \) is the initial modulus and \( E_i \) is the modulus at each cycle. We calculated \( E_i \) as the slope between 0.05\% and 0.25\% of the loading curves. Figs. 3d-f show the relationship between \( d \) and plastic strain, \( \varepsilon_p \), which is of interest because the degradation of materials is often modeled using plasticity-triggered damage [29]. Figs. 3d-f suggest the following: (i) several load cycles and relatively small \( \varepsilon_p \) (between 0.1-0.2\% for a strain rate of 0.001-0.1/s) are necessary to initiate damage; (ii) damage remains limited before the final failure; (iii) a higher strain rate increases the rate of damage; (iv) the large scatter of \( d \) without a clear
trend in the plastic strain at which damage initiates (0.20% for 0.001/s, 0.08% for 0.01/s and 0.11% for 0.1/s) is also typical for materials experiencing brittle failure. The failure behavior shown in Figs. 3d-f is in accordance with the brittle failure of IPP shown in Fig. 2.

3.2. Response of GFIPP [90]

3.2.1. Monotonic response and failure morphology

Monotonic stress-strain curves of [90] are presented in Fig. 4. The stress-strain curves are generally linear up to 0.2%. Afterwards, the curves become non-linear up to a failure point between 0.5% and 0.7%. Table 3 summarizes the transverse strength, failure strain and tensile modulus of GFIPP [90]. The tensile modulus (measured from the stress-strain slope between 0.1-0.2%) is not consistently affected by increased strain rates. The transverse modulus ranges between 4.43 and 4.63 MPa across the studied strain rates. The strain rates affecting the tensile strength at 0.001/s and 0.1/s are compared. Increasing the applied strain rate by 100 fold increases the tensile strength by 26-28% (by assuming a linear increase in the logarithmic scale).

At the macroscopic scale, failure of GFIPP [90] can be characterized by a straight fracture that is perpendicular to the loading direction. SEM images of a fractured surface of GFIPP [90] at different strain rates are shown in Fig. 5. At the microscopic scale, failure of GFIPP [90] can be characterized by matrix cracks. There is also, to a certain extent, complete fiber-matrix debonding. However, since fiber-matrix cohesion in GFIPP is strong due to amino silane, the matrix is mostly attached to the fiber and is slightly stretched. The coalescence of several matrix cracks as well as fiber-matrix debondings generally leads to complete transverse fracture. In terms of strain-rate sensitivity, there is no observable difference in the failure modes among samples tested at different strain rates.

3.2.2. Cyclic response and damage parameter

Cyclic stress-strain curves (representative curves) of GFIPP [90] are shown in Figs. 6a-c. Figs. 6d-f show the relationship between $d$ and $\varepsilon_p$ for GFIPP [90] under cyclic strain rates of 0.001/s, 0.01/s and 0.1/s, respectively. The average values of $d$ are indicated with circles connected with continuous lines; the gray shading indicates the standard deviation of the
tested specimens. The calculation of \( d \) is based on the values of \( E_0 \) (the loading slope of the first cycle between 0.05\% and 0.08\%) and \( E_i \) (the loading slope of subsequent cycles between 0.1\% and 0.2\%). It is shown that the damage in GFIPP initiates once the cyclic loading is applied, which is different from the behavior of neat IPP. A very small plastic strain (below 0.1\%) is needed for the damage to progress. As with neat PP, damage in GFIPP \([90]_8\) is also very limited before the final fracture, suggesting that transverse failure is catastrophic failure.

3.3. **Response of GFIPP \([\pm 45]_s\)**

3.3.1. **Monotonic response and failure morphology**

Fig. 7 shows the shear stress and shear strain curves for GFIPP \([\pm 45]_s\). The effect of the strain rate is obvious after the inflection (knee) point. Higher strain rates induce higher maximum shear stress. In-plane shear properties derived from the curves are summarized in Table 4. The data show that the strain rate affects all studied parameters (shear modulus, maximum shear strength and maximum shear strain). With reference to the samples tested at 0.001/s, the shear modulus increases by about 67\% when the applied strain rate is 0.1/s. A higher strain rate increases the maximum shear strength (or shear strain) by around 27\%. In this sense, the behavior of GFIPP \([\pm 45]_s\) could be considered viscoelastic-viscoplastic.

The failure mode of GFIPP \([\pm 45]_s\) is shear fracture in which two outer (+45°) plies detach from the inner (-45°) plies. Shear damage is initiated at the edges of the specimen. The point of damage initiation is indicated as the knee point of the stress-strain curve. SEM images of fractured GFIPP \([\pm 45]_s\) are shown in Fig. 8. Macroscopic shear fracture is basically characterized by shearing of the matrix protrusions around the fibers. As the strain rate increases, such protrusions become shorter due to the fact that the time required for the matrix to deform in the shear is short. Thus, the protrusion in the sample subjected to a strain rate of 0.1/s is relatively shorter than that in specimens subjected to a strain rate of 0.001/s or 0.01/s.

3.3.2. **Cyclic response and damage parameter**
Representative curves of GFIPP [±45], under monotonic and cyclic loads at various strain rates are shown in Figs. 9a-c. Figs. 9d-f show the corresponding damage in GFIPP [±45], from the cyclic tests. Figs. 9d-f show that, similar to GFIPP [90], damage in GFIPP [±45], develops very early, i.e., it starts in a single cycle. The damage rapidly increases in the region of 0-2% plastic strain, beyond which a gradual progression in damage is observed. This rapid stiffness loss is attributed to the development of diffuse damage (fiber-matrix debonding and matrix cracks). A very extensive plastic strain is needed by GFIPP [±45] as compared to GFIPP [90] to reach final failure. It is also noteworthy that the average value of \( d \) increases with increases in the applied strain rate. Physically, this may imply that the density of diffuse damage in GFIPP [±45] is higher for specimens tested at higher strain rates, and a large accumulation of damage is required for GFIPP [±45] to fail completely.

4. Conclusions

We tested impact copolymer polypropylene (IPP) and glass/polypropylene (GFIPP with matrix-dominated lay-ups of [90] and [±45]). We subjected IPP and GFIPP to monotonic and cyclic tensile loads at various quasi-static strain rates. We found that IPP exhibits viscoelastic-viscoplastic behavior and the failure is characterized by brittle fracture. GFIPP [90] seems to be insensitive to the strain rate since its failure is catastrophic (non-progressive) and mainly controlled by local defects. In contrast, GFIPP [±45] is sensitive to the strain rate and its failure strength, failure strain and modulus all change under strain (thus, GFIPP [±45] can be considered viscoelastic-viscoplastic). Based on the damage parameter \( d \) obtained from our cyclic tests, neat IPP and GFIPP [90] require relatively small plastic strain to fail due to the non-progressive nature of failure (transverse fracture of lamina), while in contrast, [±45] requires extensive plastic strain until failure due to a coupling between matrix plasticity and progressive nature of diffuse damage (matrix cracking, fiber/matrix debonding). The results reported in this paper have implications for the use of thermoplastic composites in large-scale manufacturing of automobiles.

Acknowledgments
We thank SABIC for providing research funds and raw materials. This research was also supported by Baseline Research Fund from King Abdullah University of Science and Technology. We also gratefully acknowledge research support from Mr. Warden Schijve (SABIC Netherlands), Dr. Jian Zhou (KAUST) and Prof. Bing Pan (Beihang University).

References


Table 1. Digital image correlation parameters for the GFIPP tests (M denotes monotonic; C denotes cyclic)

<table>
<thead>
<tr>
<th>Lay-up</th>
<th>Strain rate (s(^{-1}))</th>
<th>ROI (px)</th>
<th>Frame rate (fps)</th>
<th>Subset size (px)</th>
<th>Step size (px)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFIPP [90] (\theta) 0.001</td>
<td>864 x 448 (M)</td>
<td>10.26 (M)</td>
<td>85 (M)</td>
<td>10 (M)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>448x352 (C)</td>
<td>20.02 (C)</td>
<td>85 (C)</td>
<td>10 (C)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>192x160 (C)</td>
<td>31.83 (C)</td>
<td>35 (C)</td>
<td>10 (C)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>96x64 (M)</td>
<td>44.75 (M)</td>
<td>15 (M)</td>
<td>10 (M)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>96x64 (C)</td>
<td>53.98 (C)</td>
<td>15 (C)</td>
<td>10 (C)</td>
<td></td>
</tr>
<tr>
<td>GFIPP [±45] (\theta) 0.001</td>
<td>608x448 (M)</td>
<td>2 (M)</td>
<td>111 (M)</td>
<td>10 (M)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>192x192 (C)</td>
<td>4 (C)</td>
<td>35 (C)</td>
<td>10 (C)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>448x352 (M)</td>
<td>10.03 (M)</td>
<td>35 (M)</td>
<td>10 (M)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>96x96 (C)</td>
<td>41.55 (C)</td>
<td>19 (C)</td>
<td>10 (C)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>96x64 (M)</td>
<td>45.93 (M)</td>
<td>33 (M)</td>
<td>1 (M)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>96x64 (C)</td>
<td>52.10 (C)</td>
<td>33 (C)</td>
<td>1 (C)</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Monotonic tensile properties of IPP

<table>
<thead>
<tr>
<th>Strain rate (s(^{-1}))</th>
<th>Tensile strength (MPa)</th>
<th>Failure strain (%)</th>
<th>Tensile modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>21.0 ± 0.1</td>
<td>2.69 ± 0.13</td>
<td>1.75 ± 0.16</td>
</tr>
<tr>
<td>0.01</td>
<td>22.6 ± 0.1</td>
<td>3.28 ± 0.19</td>
<td>1.90 ± 0.07</td>
</tr>
<tr>
<td>0.1</td>
<td>24.4 ± 0.1</td>
<td>3.74 ± 0.72</td>
<td>1.90 ± 0.08</td>
</tr>
</tbody>
</table>
Table 3. Monotonic tensile properties of GFIPP [90]

<table>
<thead>
<tr>
<th>Strain rate (s⁻¹)</th>
<th>Tensile strength (MPa)</th>
<th>Failure strain (%)</th>
<th>Tensile modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>16.8 ± 0.6</td>
<td>0.50 ± 0.05</td>
<td>4.43 ± 0.19</td>
</tr>
<tr>
<td>0.01</td>
<td>17.4 ± 0.7</td>
<td>0.50 ± 0.05</td>
<td>4.63 ± 0.17</td>
</tr>
<tr>
<td>0.1</td>
<td>21.2 ± 0.1</td>
<td>0.64 ± 0.16</td>
<td>4.58 ± 0.30</td>
</tr>
</tbody>
</table>

Table 4. Monotonic tensile properties of GFIPP [±45]

<table>
<thead>
<tr>
<th>Strain rate (s⁻¹)</th>
<th>Maximum shear strength (MPa)</th>
<th>Maximum shear strain (%)</th>
<th>Shear modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>32.6 ± 2.1</td>
<td>32.8 ± 1.8</td>
<td>0.99 ± 0.04</td>
</tr>
<tr>
<td>0.01</td>
<td>34.4 ± 1.2</td>
<td>33.4 ± 5.4</td>
<td>1.38 ± 0.04</td>
</tr>
<tr>
<td>0.1</td>
<td>41.9 ± 1.1</td>
<td>37.9 ± 8.6</td>
<td>1.44 ± 0.11</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 1. Stress-strain curves of IPP under monotonic tensile at different strain rates

Figure 2. SEM images of fractured surfaces of IPP

Figure 3. Representative stress-strain curves for IPP under monotonic and cyclic loads for strain rates of (a) 0.001/s, (b) 0.01/s, (c) 0.1/s; correspondence between plastic strain and the damage from cyclic tests at strain rates of (d) 0.001/s, (e) 0.01/s, (f) 0.1/s. Note: the gray shading indicates the standard deviation of the tested specimens.

Figure 4. Stress-strain curves of GFIPP [90]s at different strain rates

Figure 5. SEM images of fractured surfaces of GFIPP [90]s

Figure 6. Representative stress-strain curves for GFIPP [90]s under monotonic and cyclic loads for strain rates of (a) 0.001/s, (b) 0.01/s, (c) 0.1/s; correspondence between plastic strain and the damage from cyclic tests at strain rates of (d) 0.001/s, (e) 0.01/s, (f) 0.1/s. Note: the gray shading indicates the standard deviation of the tested specimens.

Figure 7. Stress-strain curves of GFIPP [±45]s at different rates

Figure 8. SEM images of fractured surfaces of GFIPP [±45]s

Figure 9. Representative stress-strain curves for GFIPP [±45]s under monotonic and cyclic loads for strain rates of (a) 0.001/s, (b) 0.01/s, (c) 0.1/s; correspondence between plastic strain and the damage from cyclic tests at strain rates of (d) 0.001/s, (e) 0.01/s, (f) 0.1/s. Note: the gray shading indicates the standard deviation of the tested specimens.
Fig 1

Fig 2
Fig 3

Fig 4
**Fig 5**

- **Fig 5a**: Engineering stress vs. engineering strain for $\dot{\varepsilon} = 0.001$/s.
- **Fig 5b**: Engineering stress vs. engineering strain for $\dot{\varepsilon} = 0.01$/s.
- **Fig 5c**: Engineering stress vs. engineering strain for $\dot{\varepsilon} = 0.1$/s.

**Fig 6**

- **Fig 6d**: Plastic strain vs. $\phi - f_1$, $P$ for $\dot{\varepsilon} = 0.001$/s.
- **Fig 6e**: Plastic strain vs. $\phi - f_1$, $P$ for $\dot{\varepsilon} = 0.01$/s.
- **Fig 6f**: Plastic strain vs. $\phi - f_1$, $P$ for $\dot{\varepsilon} = 0.1$/s.
Fig 7

Fig 8
Fig 9