EXPERIMENTAL INVESTIGATIONS ON THE INFLUENCE OF STRAIN RATE ON MECHANICAL PROPERTIES OF DIRECT COMPOUNDED COMPRESSION MOULDED LONG FIBRE THERMOPLASTICS

Khapra, Tarun, Mohammadkhani, Pouya, Bondy, Matthew and Altenhof, William*
Department of Mechanical, Automotive and Materials Engineering, University of Windsor, 401 Sunset Avenue, Windsor, Ontario, Canada N9B 3P4
* Corresponding author (altenh1@uwindsor.ca)

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Glass and carbon Long Fibre Thermoplastics (LFTs) are gaining significant popularity as lightweight, high-performance recyclable materials, and it is essential to have a comprehensive understanding of their distinct mechanical properties. To evaluate the tensile mechanical properties of LFTs from quasi-static to elevated strain rates, up to $150{\cdot}s^{-1}$, specimens were extracted from 3mm thick flat plaques manufactured utilising a direct compounded compression moulding process. The study utilised Polyamide 66 (PA66) for the carbon fibre and Polyamide 6 (PA6) for the glass fibre-reinforced LFT materials at 40% and 30% fibre content by weight, respectively. In order to study the anisotropy, test samples were examined at two material directions of 0° and 90°, where material direction corresponds to the flow direction of the material within the mould. Tensile tests at elevated loading rates were conducted on a custom-built Intermediate Rate Tensile Test Apparatus (IRTTA). Based on the findings of this study, it was observed that the glass fibre-reinforced LFT material displayed a substantial sensitivity to strain rate. On the other hand, carbon fibre-reinforced LFT did not show any rate sensitivity for loading in the 0° material direction. However, a subtle positive rate sensitivity was observed for loading in the 90° material direction, primarily attributed to the heightened influence of the matrix in that specific material orientation. Glass fibre-reinforced LFTs showed tensile strengths of 155 MPa and 75 MPa for loading in the 0° and 90° material directions, respectively, which was notably lower than the 210 MPa for 0° and 93 MPa for 90° material directions in the case of carbon fibre-reinforced LFT for quasi-static loading. This study offers crucial material characterisation, enabling precise numerical and analytical modelling of materials.

1. Introduction

Reducing vehicle weight is of utmost importance in both the automotive and aerospace industries as it directly impacts efficiency, carbon emissions and operating costs. Recently, fibre-reinforced thermoplastic composites have been increasingly preferred over thermosets due to their ability to be reheated and reused, improved impact resistance, high fracture toughness, and recyclability, leading to reduced cost and lower carbon emission [1]. Long fibre-reinforced thermoplastics (LFT) are materials consisting of a thermoplastic polymer matrix combined with discontinuous reinforcement fibres, where the length-to-diameter ratio of the fibres exceeds the critical aspect ratio, typically exceeding 100 [2].

Several studies have been conducted to mechanically characterise LFT materials, with a focus mainly on injection-moulded parts. Limited research is available in the open literature on compression moulded carbon and glass-reinforced LFTs, especially at higher loading rates [3-6]. Composites exhibit a complex mechanical response when subjected to dynamic loading conditions due to their sensitivity towards the deformation and failure processes at higher loading rates. Carbon fibre is known to be strain rate insensitive, and various studies have documented those properties for carbon fibre composites [7]. On the other hand, for glass fibre-reinforced composites, tensile strength, toughness, and maximum strain increase with strain rate at room temperature. Additionally, the properties of composites are significantly affected by environmental factors such as moisture [8].

This study analysed direct compounded compression moulded carbon and glass fibre-reinforced LFT materials. To assess their behaviour under different conditions, quasi-static and intermediate-rate dynamic uniaxial tensile tests were conducted. These tests were performed in two directions, at 0° and 90° relative to the flow direction. The experimental findings provide a comparative analysis of the carbon and glass fibre-reinforced LFTs in terms of their mechanical characteristics under various loading rates. This study aims to enhance comprehension of these materials when subjected to higher loading rates and elucidate the variations in their behaviour. Such insights will enable designers to incorporate these lightweight structures efficiently.

2. Materials and Methods

2.1. LFT-D process and materials

The direct compounded long-fibre thermoplastics (LFT-D) specimens for both carbon fibre and glass fibre material examined in this study were fabricated at Fraunhofer Innovation Platform for Composites Research at Western University in London, Ontario. The production of flat plaques was carried out on the Diffenbacher LFT-D manufacturing line, which involved two main processes: compounding and moulding. The compounding phase involves the formation of molten LFT charge using thermoplastic granules, chopped fibres and additives. The LFT charge is then transferred to the moulding press, where the final structure is formed; this manufacturing process is represented in Figure 1.

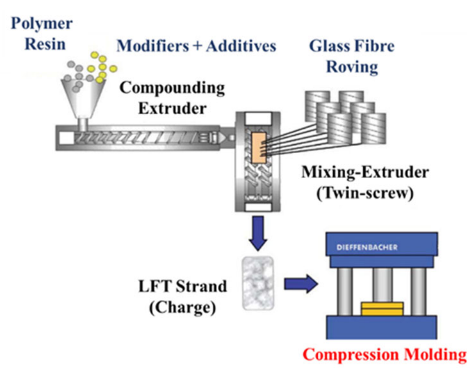


Figure 1. Schematic of direct compounding and compression moulding process for manufacturing LFT materials [8].

In the compounding process, PA66 granules for carbon fibre-reinforced LFT and PA6 for glass fibre-reinforced LFT were fed into the compounding extruder (ZSE), where the granules were melted and homogenised. The molten polymer was then introduced to a co-rotating twin screw extruder (ZSG Leistritz ZSG-75 P-17D) via a waterfall die. The fibres were chopped and fed into the ZSG until the fibre content reached 40wt% for carbon fibre and 30wt% for glass fibre. Both the extruders were co-rotating twin-screw equipped with electrically heated sections to facilitate the melting of the polymer during extrusion.

The matrix material used for the study was supplied by BASF ®. Ultramide A3W polyamide 66 was used for carbon fibre LFT, and Ultramid 8202 HS low-viscosity heat-stabilized material was used for glass fibre LFT. The carbon fibre employed was Zoltek Panex3 5-62, and in the case of glass fibre, StarRov 886RXN by Johns Manville ® with a 16 µm filament diameter was used. In the moulding phase, the Diffenbacher DCP-U 2500/2200 press was used to obtain the flat plaques (460mm by 460mm with a nominal thickness of 3mm) from the molten LFT charge.

2.2. Sample preparation

Samples for both types of material were extracted from the flat plaques using waterjet cutting. The cutting process led to significant moisture absorption within the samples through sorption. The samples underwent a drying process with slight differences in drying parameters for carbon fibre and glass fibre LFT. The carbon fibre samples were dried in a vacuum oven at 100 °C at a vacuum of 70kPa for one week until a steady state mass reduction of approximately 0.75% was recorded. The glass fibre samples were dried at 80 °C and under the same vacuum pressure for nine days. The dried carbon and glass fibre-reinforced samples were stored in sealed desiccator bags to prevent any alteration due to moisture in the atmosphere until they were tested.

2.3. Experimental methods

2.3.1. Quasi-static uniaxial tensile testing

Baseline quasi-static tensile tests were conducted utilising a 50kN capacity MTS Criterion (model 43) electromechanical universal testing machine at orientations of 0° and 90° with respect to the flow direction for both materials. An MTS video extensometer equipped with a Nano-M1450 camera sampling from 5 to 75Hz was utilised for strain measurement within the gauge region. In the case of carbon fibre-reinforced LFT, the crosshead speed of 1mm/min was maintained in order to achieve a strain rate between 10^{-5} s^{-1} and 10^{-4} s^{-1}1 in the gauge region. The specimen geometry used was ASTM D638 Type III, with a reduced gauge length (6.25mm). For glass fibre/PA6, the cross speed was maintained at 0.5 mm/min and 5 mm/min to achieve strain rates of 10^{-4} s^{-1} and 10^{-3} s^{-1}, respectively, in the gauge region. The specimen geometry utilised in this case was ASTM D638 Type V.

2.3.2. Elevated strain rate tensile testing

Elevated loading rate tensile tests were conducted on a custom-built novel Intermediate Rate Tensile Test Apparatus (IRTTA), the schematic of which is shown in Figure 2.

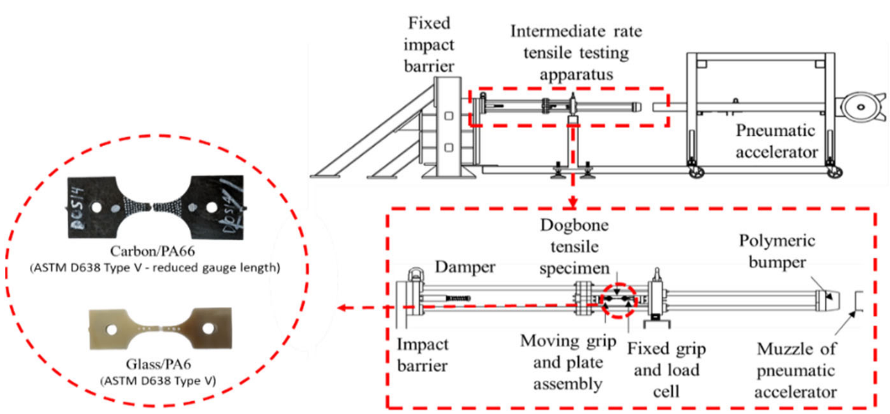


Figure 2. IRTTA apparatus utilizing the impact barrier schematic and intermediate rate specimen geometry [9].

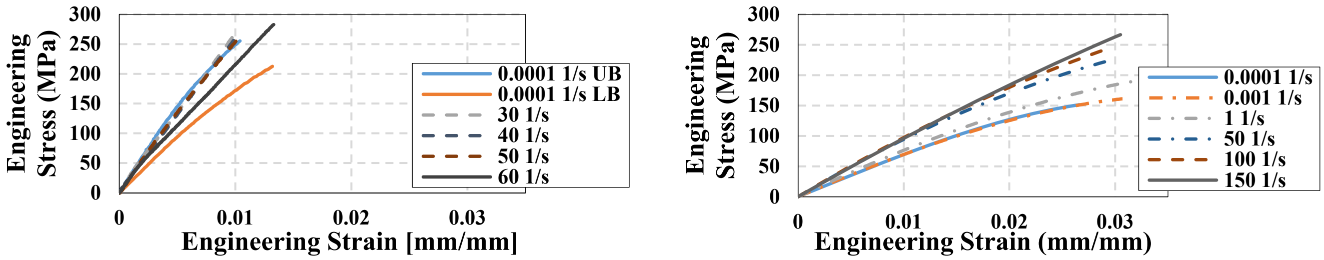
The IEPE load cell powered by a PCB 484B06 signal conditioner (AC coupled) was used with a NI 9223 module in a CompactDAQ chassis to acquire force/time data at 1 MHz. Strain measurements were acquired by post-processing the images obtained from a Photron Fastcam SA4 high-speed camera with Correlated Solutions ® VIC-2D DIC and ProAnalyst software. Custom designed LabVIEW code was used to synchronise the TTL trigger for the high-speed camera and data acquisition from the load cell with the projectile by utilising laser displacement transducers for the detection of the projectile. The specimen geometry utilised for carbon fibre and glass fibre LFT was ASTM D638 Type V with the modified gripping region to allow the fasteners to clamp the specimen [9]. In the case of carbon fibre LFT, the gauge length was also reduced from 9.53 mm to 5 mm in order to achieve higher strain rates.

The specimen geometry also conforms to the SAE draft standard for dynamic loading, which requires 10 to 15 elastic wave reflections through the gauge length between the start of dynamic loading and yielding [10].

3. Results and Discussions

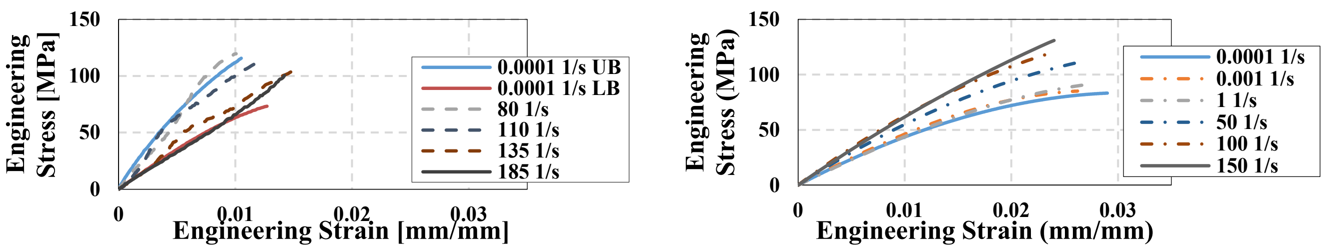
3.1 Quasi-static and elevated strain rate loading tests

Figure 3 presents the engineering stress-strain responses for both the materials and their dependency on fibre orientation and loading rate. In the quasi-static regime, carbon/PA66 outperforms glass/PA6 in terms of strength in both material directions. The engineering stress/strain responses of carbon/PA66 showed no significant rate effect, while it was evident in the case of glass/PA66. The intermediate strain rate results lay within the upper bound (UB) and lower bound (LB) of the response obtained via quasi-static tensile tests, which suggested carbon/PA66 was insusceptible to strain rate. On the other hand, enhancement of mechanical properties was observed in the case of glass/PA6 with the increase in loading rate (from 0.0001 s^{-1} to 150 s^{-1}).



(a) (b)

Figure 3. Engineering stress-strain responses of 0° material direction for (a) carbon/PA66 and (b) glass/PA6.



(a) (b)

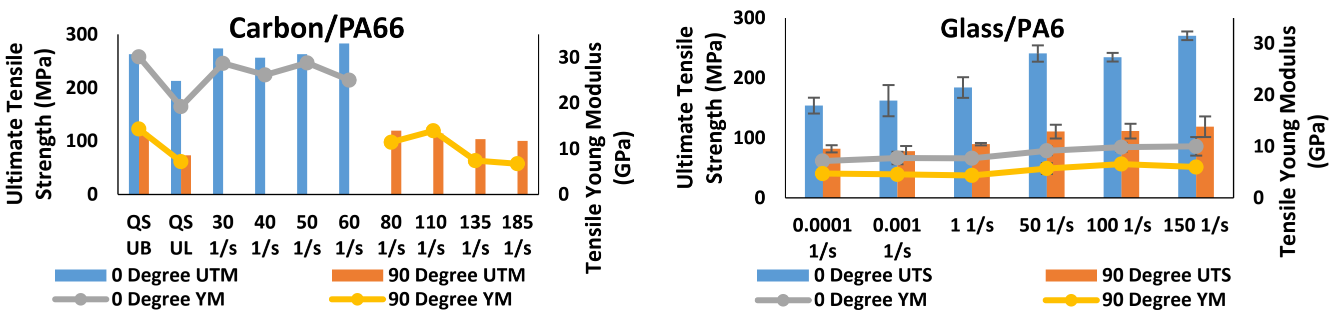
Figure 4. Engineering stress-strain responses of 90° material direction for (a) carbon/PA66 and (b) glass/PA6.

Both materials, glass/PA6 and carbon/PA66, exhibited vastly different strains to failure. Compared to carbon/PA66, glass/PA6 showed significant elongation before failure. In both materials, a significant reduction in mechanical properties was observed in the case of 90° material direction. The strength of both the material was observed to have halved due to a lack of fibre orientation in this direction.

3.2 Influence of elevated strain rates on mechanical properties

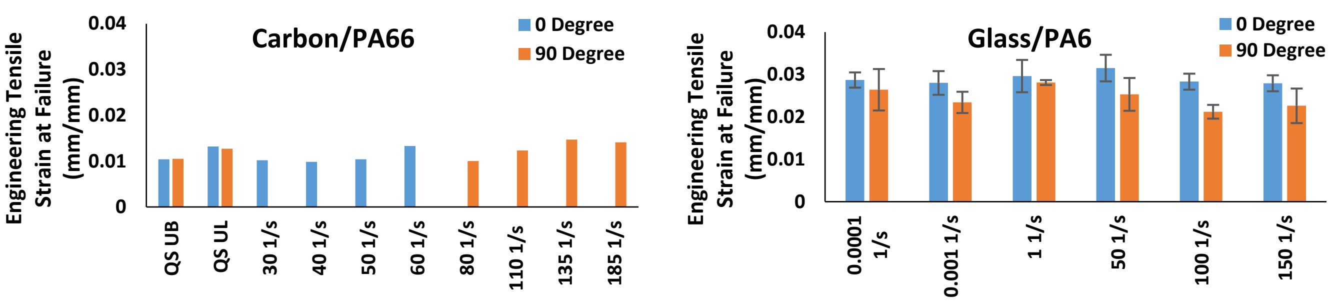
Effects of elevated rate loading on the mechanical properties were examined for both carbon/PA66 and glass/PA6 in 0° and 90° material directions. Due to the limited availability of carbon/PA66 material, only a restricted number of tests were conducted, leading to the absence of error bars in the graph. Furthermore, the scarcity of this material constrained testing across different loading rates. Divergent responses in ultimate tensile strength (UTS) and Young's modulus (YM) to varying strain rates are evident when comparing carbon and glass LFT materials, as illustrated in Figures 5(a) and 4(b). Notably, the ultimate strength of carbon/PA66 remained largely unchanged for 0° material directions, but a 63% increase was observed for 90° material direction, indicating the stronger influence of the matrix in this material direction. In contrast, glass/PA6 exhibited a substantial enhancement in ultimate tensile strength when subjected to higher strain rates, particularly in the 0° material direction. A consistent rise in ultimate tensile strength was noted as the strain rate escalated from quasi-static (QS) loading to the highest rate of 150 s^{-1}, resulting in a remarkable 97% enhancement in strength. In the 90° material direction, only a marginal increase in strength was observed.

Carbon/PA66 demonstrated a notably higher Young's modulus in both material directions compared to glass/PA6. In the case of carbon/PA66, a slight improvement in modulus was observed in the 90° material direction, but the response for 0° material direction was similar irrespective of strain rate. A significant increase of 76% in Young's modulus was observed for 0° material direction when the strain rate increases from 0.0001 s^{-1} to 150 s^{-1} for glass/PA6. Improvement in the 90° material direction was slightly lower than the 0° material direction.



(a) (b)

Figure 5. Ultimate strength and Young's modulus response of (a) carbon/PA66 and (b) glass/PA6 LFT materials for two material directions at various loading rates.



(a) (b)

Figure 6. Strain at failure response of (a) carbon/PA66 and (b) glass/PA6 LFT materials for two material directions at various loading rates.

Figures 6 (a) and (b) present strains to failure for both the materials in two material directions. Carbon/PA66 showed a much lower elongation before failure, whereas glass/PA6 experienced almost threefold elongation compared to carbon fibre LFT. Within each material group, slight variations were observed. In the case of the carbon/PA66 at the 90° material direction, the LFT experienced a slight increase in elongation with an increase in strain rate, while no correlation is evident between elongation and strain rate for the 0° material direction. Glass/PA6 elongated around 3% and 2.5% for 0° and 90° material directions, respectively. Loading at a higher rate had little to no effect on elongation in either of the material directions.

4. Conclusion

This study investigated the mechanical responses of carbon/PA66 and glass/PA6 Long Fiber Thermoplastic (LFT) materials under quasi-static and elevated strain rate loading conditions. Carbon/PA66 demonstrated superior strength over glass/PA6, with minimal rate dependency, while glass/PA6 exhibited strain rate sensitivity. Carbon/PA66 showed minimal change in ultimate strength at 0° material direction but a 63% increase at 90°, while glass/PA6 exhibited a significant strength enhancement, especially at higher strain rates, with a remarkable 97% increase at 0° and marginal increase at 90° material direction. Carbon/PA66 displayed consistent Young's modulus response in the respective material directions at all strain rates considered in this investigation, while glass/PA6 exhibited a 76% increase in modulus for the 0° material direction with increasing strain rate and slightly lower in the 90° direction. Carbon/PA66 exhibited significantly lower elongation before failure compared to glass/PA6, which experienced nearly threefold elongation. Carbon/PA66 showed a slight elongation increase at a 90° material direction with strain rate increase.

Acknowledgements

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