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Low velocity impact testing of direct/inline compounded carbon fibre/polyamide-6 long fibre thermoplastic

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ABSTRACT

Direct/in-line compounded PA6/CF long fibre thermoplastic was characterized under low velocity impact consistent with ISO standard 6603-2. Additionally, a quasi-static variant of the ISO method was employed to indirectly assess rate sensitivity. At quasi-static loading rates, flow region specimens were notably more brittle considering the force-deflection response. However, the energy absorption did not differ significantly between charge and flow region specimens. Puncture energy increased an average of 0.5 J per 1% increase in fibre weight fraction. Maximum force increased approximately 50 N per 1% increase in fibre weight fraction. Under low velocity impact, consistent trends in terms of puncture energy and maximum force between charge and flow region specimens were noted. Puncture energy increased 0.6 J and 0.4 J per 1% fibre weight fraction for charge and flow region specimens respectively. Maximum force increased 75 N and 60 N per 1% increase in fibre weight fraction for charge and flow region specimens. In terms of rate sensitivity, puncture energy under low velocity impact decreased by 18% on average with respect to quasi-static loading.

1. Introduction

Carbon fibre reinforced thermoplastic matrix composites can offer optimal combinations of specific stiffness, specific strength, fatigue performance, and recyclability. The latter is a particularly critical characteristic in the European market which requires 95% recoverability and 85% recyclability. Mechanical characteristics are enhanced by increasing fibre length; for discontinuous fibre composites direct compounding and compression molding can result in less fibre length degradation than other processes. Such materials can be categorized as long fibre thermoplastics (LFTs) if the fibre aspect ratio is greater than 100 which is roughly equivalent to a fibre length of 1 mm.

2. Literature review

Early research on LFT materials focused on polyamide (PA) matrices [1-4]. However, commercial success has primarily been realized with polypropylene (PP) where glass fibre (GF) is the dominant reinforcement [5-7]. Global LFT consumption is approximately 200 000 tonnes annually with 80% consumed by the automotive industry and 60% of manufacturers located in the EU [8]. Direct/in-line compounding, though versatile in terms of fibre/matrix material combinations, entails high capital costs and requires highly qualified personnel to identify suitable process parameters. Capital costs are approximately €1 million; as a result the process is economical with a production rate in excess of approximately 500 000 kg annually [9].

A much larger knowledgebase is available in the open literature for mechanical properties of glass fibre LFT materials. While some conclusions from such research may be applicable, the relatively low stiffness of glass fibre with respect to its strength may yield reduced material performance in terms of impact and fatigue with respect to carbon fibre (CF) reinforcement. Thomason [10] investigated the impact performance of dry-as-molded and boiling water conditioned injection molded glass fibre (10, 14, and 17 μm diameter; 10–50% by weight) and PA 66. The product of fibre aspect ratio and volume fraction indicated a random fibre orientation during melt processing limited the fibre length in the molded part. Notched and un-notched specimens were characterized; notched specimen impact characteristics were effectively independent of fibre diameter. Un-notched specimen impact performance was not strongly influenced by fibre length.

Bartus and Vaidya [11] subjected compression molded LFT-G (granule) PP & GF specimens to blunt object intermediate velocity (40–140 m/s) impact to obtain a critical velocity where 50% of projectiles do not perforate the specimen (similar to the V_{50} ballistic limit but applied to low velocity impact). One critical conclusion was that the material did not exhibit significant rate sensitivity under the conditions of the study. Another finding applicable to the current

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work is the strong indication of fibre orientation influencing impact characteristics.

In a rare investigation of direct compounded long fibre thermoplastic materials, Zhang et al. [12] of the National Research Council of Canada characterized the mechanical properties of both compression and injection molded PP/GF and PA/GF materials (4 different configurations) under low velocity impact. A significant decrease in stiffness was observed at +85 °C with respect to room temperature. However, the force-deflection responses prior to maximum load were minimally affected by temperature in the range of −40 °C to 0 °C. With a PP matrix, injection molded parts were observed to have lower maximum loads with respect to compression molded parts. In terms of damage/failure mechanisms, PP was minimally affected by temperature. Less damage was observed for PA/GF at higher temperatures.

Rate sensitivity has directly been assessed with servohydraulic testing machines and uniaxial tensile tests. Schossig et al. [13] completed tensile tests on glass reinforced thermoplastics at strain rates of 0.007 s^{-1} and 174 s^{-1}. Positive strain rate sensitivity, consistent with the literature, was observed. Two sets of parameters for the G'Sell-Jonas model [14] were identified (a transition from isothermal to adiabatic behaviour occurs). However, anisotropy (which can be significant for compression molded LFT materials) is not considered. Weeks and Sun [15] assessed the rate dependence of mechanical properties of AS4 CF/PEEK thermoplastic. Tests were conducted on balanced angle ply specimens with orientations of 0°, 15°, 30°, 45°, and 60° with a servohydraulic testing machine (strain rates between 10^{-5} and 0.1 s^{-1}) and a split Hopkinson pressure bar (SHPB) (100–1000 s^{-1}). Two rate dependent constitutive models were developed.

The open literature includes few, if any, studies of the mechanical properties of compression molded, direct compounded carbon fibre reinforced thermoplastic. Impact data is particularly scarce. The current study is a first step in developing a better understanding of the influence of process configuration and material formulation on impact properties for this type of material through the use of an industry standard test. While Charpy impact may be the more popular method for assessing impact properties, there are concerns that for longer fibre lengths the small size of a Charpy specimen may introduce a dependence of mechanical properties on specimen size. Therefore, the ISO 6603 puncture test was selected rather than a unique apparatus (i.e. Bartus et al.) which would introduce challenges in comparisons with data in the literature.

3. Methodology

3.1. Specimen preparation

Carbon fibre/PA6 material was manufactured by the Fraunhofer Project Centre in London, Ontario on a Dieffenbacher LFT-D manufacturing line. Approximately seven 458 mm by 458 mm by ~2.7 mm square plaques were provided for each of eight process configurations which are documented in Table 2. Material with fibre weight contents (Toho Tenax HTR40 F22 1550tex, 24k tow count) of 9, 12, 18, and 25% were produced. Note that this is a fibre with epoxy sizing. Subsequent research has employed carbon fibre intended for the selected matrix material. The matrix was BASF 8202 heat stabilized (HS) polyamide 6. Charge placement was asymmetric as shown in Fig. 1(a) with a mold coverage of approximately 14%. Charge mass was defined in the manufacturing process control software to be 755 g with approximate dimensions of 100 mm by 300 mm by 20 mm. The press force was 5000 kN with the speed-distance profile shown in Table 1. The mold temperature was 120 °C and the cooling time was 30 s.

The specimens were conditioned at room temperature and an approximate relative humidity of 30%. Details in moisture absorption can be found in [16]. Specimens were extracted by water jet at DYDD Systems in Oldcastle, Ontario at a pressure of 345 MPa with a nozzle diameter of 0.076 mm. Six 140 mm by 140 mm ISO 6603-2 impact specimens were extracted from each plaque as shown in Fig. 1(a): three from the flow region and three from the charge region. Four plaques from each process configuration were prepared to obtain 12 specimens from each region for each process configuration: 6 for quasi-static characterization and 6 for low velocity impact.

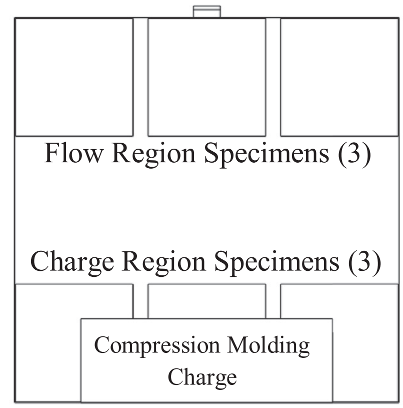

Fig. 1. ISO 6603-2 specimen layout and charge placement.

3.2. Quasi-static characterization

Uniaxial tensile and flexure (three point bending) testing for this material are documented in [16]. To study this material under a more complex stress state and indirectly assess rate sensitivity (by comparison with low velocity impact), quasi-static loading with a hemispherical indenter was completed consistent with the geometry in the ISO 6603-2 instrumented impact standard. In contrast to tensile tests the puncture test subjects the region of the specimen inside the clamping ring to a complex 2D stress state (transitioning between biaxial tension and flexure). Additionally, there is a localized 3D stress state where the specimen contacts the indenter. A fixture was constructed compatible with an MTS Criterion Model 45 electromechanical load frame equipped with a 150 kN load cell. The striker was lubricated with PC Waylube 68 (viscosity of 69.7 cSt at 40 °C; ISO 6603-1 recommended range: 10–10 000 cSt) for both quasi-static and impact tests. Images for observing damage/fracture propagation were acquired with an MTS Advantage video extensometer (Allied Vision Mantra 1.3 MP camera with a frame rate of 2 fps). The loading rate was 2.6 cm per minute (1% of the nominal low velocity impact speed of 4.4 m/s) to a deflection of 25 mm.

3.3. Low velocity impact

Low velocity impact testing was completed consistent with the ISO 6603-2 standard on a custom drop tower equipped with suitable fixtures. Specimen deflection was measured with an Acuity 300 mm (30 mm/V sensitivity) laser displacement transducer acquiring the

Table 1
Speed-distance profile for compression molding.

Speed (mm/s)	Distance (mm)
75	50
35	35
15	15
10	0