MECHANICAL BEHAVIOUR OF 3D PRINTED COMPOSITE MATERIALS

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ABSTRACT
A fused deposition modelling 3D printer device was employed to fabricate 3D polymeric composite structures in order to evaluate their mechanical properties. Several experimental test methodswere used in the current workto characterize the mechanicalbehaviour ofneat polyethylene terephthalate glycol (PETG) and PETG reinforced with carbon fibres. To determine the static compression stiffness and hysteresis of the specimens, compression and cyclic tests were conducted. Considering the obtained results,PETG's stiffness was improved with the embedded ofcarbon fibres,while its damping capacity wasmoderately reduced.

Keywords: Additive manufacturing, mechanical properties, PETG, carbon fibres

1. INTRODUCTION

Due to global competition and product mass customization, the manufacturing industry is now under more pressure to look for and take advantage of processes that can provide flexibility and cost savings to cope with small batches and rapid product changes. 3D printing processes have had a tremendous impact on the field of design, in the form of rapid prototyping and toolmaking and, more recently, part production. One of the mostly used technique is the Fused Deposition modelling (FDM) which usesa thermoplastic filament as a building material.This particular technique has caught hold in the hobbyist and do-it-yourself communities withthe availability of low-cost machines that are approaching the part quality capabilities of commercialmachines. In FDM the filament is pushed through a heated extrusion nozzle, causing the material to melt and deposited layer-by-layer until a 3D object is created [1].

The available materials are generally limited to ABS, PLA, Nylon,and Polycarbonate, with bulk strengths between 30–100 MPa and elastic moduli in the 1.3–3.6GPa range with those numbers greatly reduced in printed components [2-4].However, recently more materials have been used in 3D printing processes and novel materials are now fabricated incorporating fibres with unique characteristics [5]. The FDM 3D printing takes advantage of such novel materials produced by combining the base matrix material with micro-size additives in specific concentrations and structures. Novel 3D printed materials might result in a range of unidentified mechanical properties of the final part. While there is a perception that such novel materials provide superior mechanical properties, still there is a need to provide reliable mechanical data following appropriate tests.

In the current paper the commercially grade polyethylene terephthalate glycol (PETG) and PETG with micro carbon fibres are evaluated using compression tests and cyclic compression tests. The stress-strain graphs are obtained and the modulus is measured, while from the loading-unloading cyclic compression curves the loss factor is calculatedin order to determine the reinforcing capability of the carbon fibres in a 3D printed state.

2. MATERIALS AND QUASI-STATIC EXPERIMENTAL METHODS

2.1. Manufacturing of 3D printed compositesspecimens

The main material that have been used in the current paper is the HDglass™ which is an amorphous and high strength modified PETG. Such material was provided in a filament form from Formfutura, Holland. The HDglass™ has a very impressive transparency as it is an amorphous filament, which lets 90% of the visible light pass through its fibre and has less than 1% haze. On the other hand the CarbonFil™ provided by the same company is a light-weight and noticeably stiff carbon fibre reinforced filament. The CarbonFil™ filament is based upon a blend of an HDglass™ compound reinforced with 20% ultra-light and relatively long stringer carbon fibres, which has results in an exceptionally stiff carbon fibre 3D printer filament.According to the manufacturer, by making use of the ultra-lightweight and relatively long carbon fibre stringers they have managed to make the CarbonFil™ twice as stiff as theHDglass™ compound, while they have managed to increase its impact strength with more than 10%. Usually an upturn in a material's stiffness will have a downturn on its impact strength. Due to the relatively high percentage of 20% long stringer carbon fibres in the CarbonFil™ compound there is a relatively high heat deflection temperature of 85°C and very good dimensional stability properties.

All specimens tested in this study were produced on a ZMorph SX open source printer with a 1.75 mm extrusion nozzle. Only system integrated(default) variations of production parameters were employedin the comparative analysis. As time is a key determiningfactor for productivity, printing velocity is often selected based on qualityindependent factors (i.e. production cost). Deposition speed wastherefore not considered a variable in this study and a constant extrusionvelocitywas selected for all specimens, based on device parameters(e.g. effective printing range).

At least five 3D printed specimens were prepared for HDglass™ (PETG) and CarbonFil™(Carbon/PETG). Subsequently, compression test specimens were also manufactured with dimensions of Φ29 diameter and 12.5mm height.

2.2. Compressiontests

Uniaxial compression tests were conducted using a computer controlled servo-hydraulic single axial test machine, Zwick equipped with a 100kN load cell.The compression test was carried out according to ASTM D395 standard [6]. Specimens were compressed between hardened steel compression platens containing a spherical seat to overcome any small misalignment along the load train. Lubrication was applied on the surfaces of both upper and lower platens. The test specimens were placed between the moving head and fixed head of the tensile test machine where the compressive strain in this test reached up to60% of the original specimen length. The strain rate was set at 5mm/min. The stress–strain test was respectively repeated five times forPETG and Carbon/PETG samples.

2.3. Cyclic compression tests

Steady state, strain rate–controlled cyclic compression tests at ambient temperature were performed with constant strain rates in loading and unloading. The measurement was carried out using a material testing system (Testometric, UK equipped with a 50 kN load cell) at a frequency of 0.1 Hz and up to a 6 kN load. The loss of energy in each cycle was calculated from the hysteresis loop. In the quasi-static regime, the stress-strain behavior during loading and unloading was obtained and each polyurethane demonstrated a hysteresis behaviour. The loading and unloading speeds were set constantly at 5 mm/min. The cyclic compression 3D printed specimens had the same dimensions with the compression tests.

3. RESULTS AND DISCUSSION

3.1. Mechanical properties of the 3D printed composites

The morphology of a neat PETG and a Carbon/PETG3D printed specimenswere studied using a Zeiss Stemi 2000-C stereomicroscope as shown in Fig.1 Clearly, the insertion of carbon fibres had a profound effect on the overall microscopic appearance and surface texture of the 3D printed samples. This difference is also depicted quantitatively in the stress-strain curves under uniaxial compression as shown in Fig.2. For the same stress, it is found that the correspondingstrain of the composite is lower than that of neat PETG. Evidently, the modulus of the composite was also improved by the addition of the carbon fibers. Overall, this trend can be attributed to the softness of the polymer chain structure of neat PETG and the stiffness of the carbon fibers. This is also depicted in Fig. 3 where during compression the 3D printed Carbon/PETG struts locally bended and fractured in a tensile mode during testing with small detachment. Such results indicate that Carbon/PETG composite systems exploit the properties of one component to overcome the weakness of the other in mechanical performance.

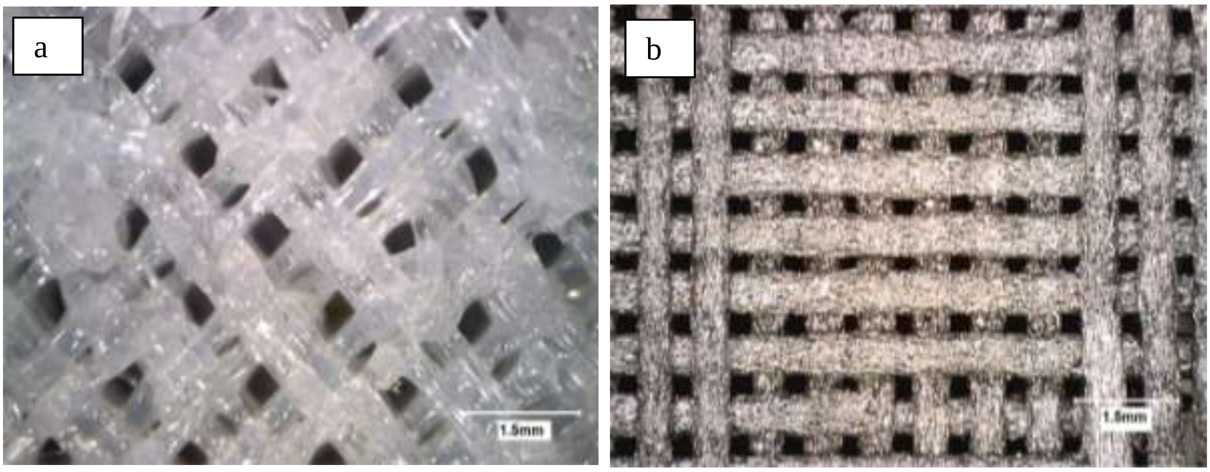

Fig. 1: Morphology for PETG and Carbon/PETG3D printed specimens.

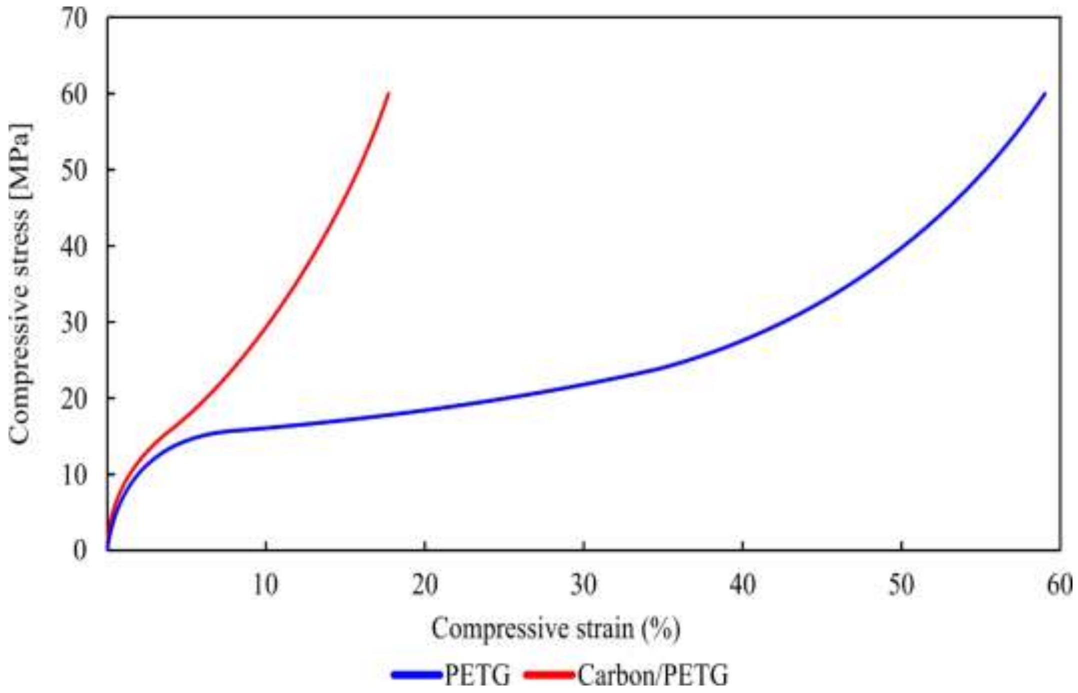

Fig. 2: Stress-strain curves for PETG and Carbon/PETG specimens.

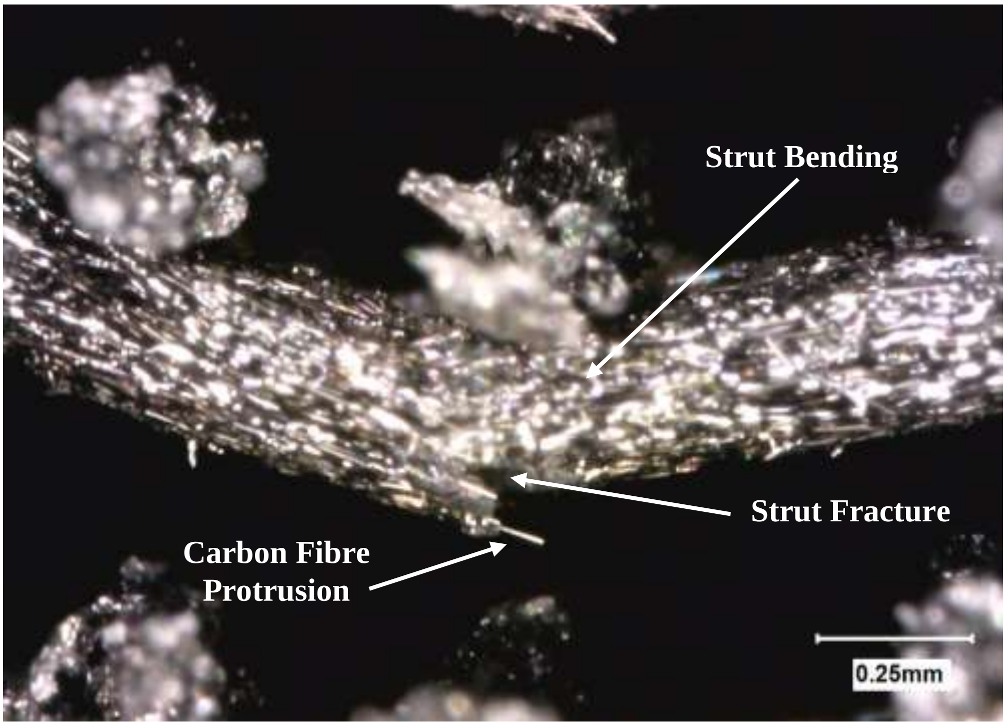

Fig. 3: Bending and fracture of the 3D printed carbon/PETGstrut.

3.2. Hysteresis of the 3D printed materials

Under alternating stress, hysteresis occurs when the rate of deformation is less than the rate of stress variation. In this case, since the absorbed and released energies are not balanced in each cycle, the stretching and recoil curve form a closed loop, which is known as a hysteresis loop. The area within the loop represents the energy loss. For polymeric materials, a larger hysteresis loop means higher damping, which more effectively reduces vibration [7]. The damping constants may be derived from the area surrounded by hysteresis loops. Based on the theory of free vibration, the vibration-isolating capacity of materials can be evaluated from the damping constant and the hysteresis damping characteristics.

The specific damping capacity (SDC) is given by:

$$SDC = \frac{\Delta W}{W} \times 100\% = \left(\oint \sigma d\varepsilon \Big/ \int_{\omega t=0}^{\pi/2} \sigma d\varepsilon \right) \times 100\% \qquad (11)$$

where σ is the stress, ΔW is the energy dissipated in any one cycle and W is the maximum energy associated with that cycle. The specific damping capacity can be related with the loss factor by:

$$n = \frac{\Delta W}{2\pi W} \qquad (12)$$

Fig.4 presents the hysteresis loops curves of 3D printed composite specimens under compressive vibration at 0.1 Hz with an ultimate force of 5 kN. Considering Eq. 12, the energy loss over a cycle (ΔW), the maximum energy of that cycle (W) and loss factor (n) were used to measure the material damping of the loading–unloading tests, as shown in Table 2. ΔW indicates that the anti-vibration property of PETG is improved as the amount of carbon fibers increases from 0 to 20wt%. Therefore, the material is assumed to enhance the ability to transform its kinetics to those of thermal dissipation upon the application of an external load. Simultaneously, it has been already observed that adding carbon fibers increases the stiffness, as shown from the stress-strain slopes in Fig.1 and 2. However, higher damping constant n, which is the ratio ofΔW to$W$, is observed for neat PETG specimens and this indicates faster energy dissipation at particular amplitudes, which become stable with less vibration.The loss factor for the PETG specimens was calculated 17.3%, while 15.4% for Carbon/PETG specimens.

4. CONCLUSIONS

The mechanical properties of PETG modified with carbon fibers were investigated with static and cyclic compression. The Carbon/PETG composites were at first tested under uniaxial compression. The elasticity modulus values of TPU/MWCNTs TPEs increased monotonically with the addition of carbon fibers. Cyclic compression test results showed higher damping constant for Carbon/PETGspecimens, which indicated faster energy dissipation at particular amplitudes, so they become stable with less vibration. Overall, the static stiffnesscan be increased by embedding carbon fibers in PETG, while the inclusion of carbon fibers in PETG resulted in moderate reduction of the damping capacity.

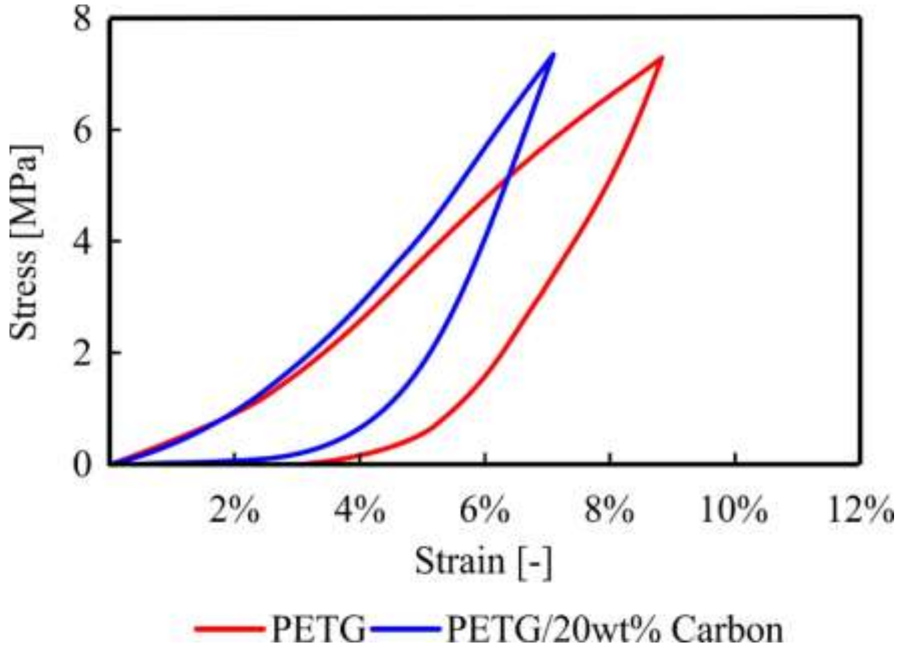

Fig. 4: Hysteresis loops for PETG and Carbon/PETG specimens.

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