3D Printed PLA/Carbon Black Constructs for Self-sensing Applications: a Novel Characterization Framework

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INTRODUCTION

3D-printable conductive polymers have gained interest in the scientific community for diverse applications, including pressure sensors, interference shielding, flexible electronics, and damage detection. One strategy for making polymers conductive involves the embedding of functionalizing fillers, such as metal nanoparticles or carbon products (*e.g.,* carbon nanotubes, nanofibers or nanoparticles), within a polymer matrix. Fillers are added in an amount exceeding a minimum threshold to allow the formation of a conductive path within the material. Any disturbance of such path, *e.g.,* due to mechanical stresses, causes a change in the material's electrical response; such phenomenon is called piezoresistivity[1]. Due to the complex microstructure of polymer nanocomposites (PNCs), which is highly dependent on the manufacturing process used, *in situ* health monitoring systems are promising solutions to predict the failure mechanisms and residual lives of such materials under varying external loads[2]. Specifically, self-sensing, as inherent ability of a material to detect damage-induced structural changes without the use of external sensors, is a functionality of great interest for the development of smart materials. In this context, additive manufacturing offers high design flexibility and low costs for PNCs processing, allowing the design of structures that leverage the anisotropy induced by the manufacturing process[1]. In the literature, experimental data on the piezoresistivity of PNCs has been widely reported, mainly focusing on strain sensing applications. Damage sensing, instead, has been less explored. Also, it is not well understood how the onset of permanent damage correlates to the change in the electrical response for this material class. Specifically, it is not clear: (i) whether 3D printed PNCs can be used for damage sensing (yielding, fatigue) together with strain sensing applications, (ii) what characterization framework can be used for this purpose, and (iii) how the damage behaviour changes with printing layup. In this work, considering some key aspects of polymer mechanics, we characterise the mechanical and electromechanical properties of a 3D printed polylactic acid (PLA)/carbon black (CB) nanocomposite material to investigate its potential for damage sensing applications. PLA/CB specimens were manufactured following ASTM D3039/D3039M[3] using fused filament fabrication and a commercial filament. After manufacturing, electromechanical tests were performed, using a Source Measure Unit (SMU) to measure samples' electrical resistance during uniaxial tensile testing. The SMU was used to supply direct current while measuring samples' resistance using a 4-wire measuring setup. Later, due to the viscoelastic nature of the material, uniaxial strain recovery tests were performed to identify the onset of permanent damage. Finally, loading-unloading electromechanical tests were carried out to further investigate the correlation between the mechanical damage and electrical properties of the material together with electrical fatigue effects. Due to the strain rate dependent mechanical behaviour of the material used, all tests were performed under displacement control using a constant strain rate.

RESULTS AND DISCUSSION

In Figure 1(a) results of the uniaxial electromechanical tests to failure are shown in terms of (engineering) stress and normalised resistance variation ($\Delta R/R_0 = (R-R_0)/R_0$) as function of (engineering) strain, together with the broken specimens (Figure 1(b)).

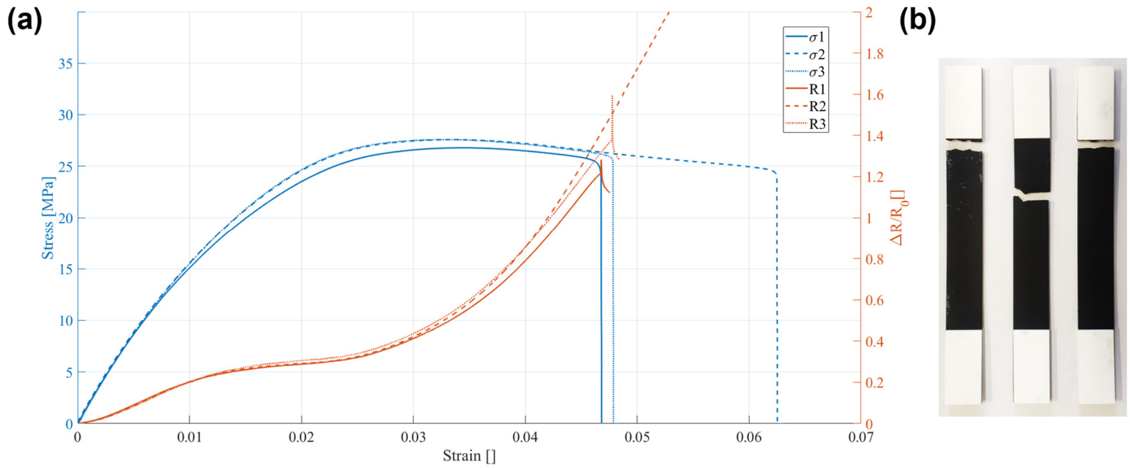

Figure 1: (a) Electromechanical test results for the samples tested (σ indicates stress and R electrical data for each of the 3 specimens) and (b) specimens after break; white PLA tabs were used to electrically insulate the specimen from the mechanical testing machine.

The electrical results ($\Delta R/R_0$) showing a non-monotonic behaviour with strain demonstrate that a correlation exists between the damage state of the printed material, later investigated through mechanical-only strain recovery tests, and the change in electrical resistance of the samples, observed during uniaxial electromechanical tests to failure (Figure 1(a)). This is further confirmed by electromechanical loading-unloading tests results, thus suggesting that the studied PLA/CB construct can successfully sense the onset of permanent damage. Overall, this work demonstrates the damage sensing capabilities of additively manufactured PLA/CB samples and presents a novel framework for characterising the damage sensing properties of PNCs. This research paves the way towards a better understanding of the damage mechanisms of PNCs and their electromechanical behaviour for damage sensing applications. With the potential to be extended to a multitude of polymeric materials, this work contributes to the development of cost-effective, tuneable, 3D printed smart structures.

REFERENCES

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