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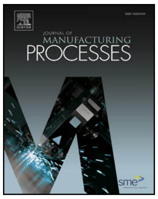

Strain sensing behaviour of 3D printed carbon black filled ABS

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ABSTRACT

Carbon Black filled Acrylonitrile Butadiene Styrene (ABS) was used to prepare a polymer composite by Fused Deposition Modeling (FDM) technology. The effect of printing setup on the strain sensing behavior of the composite was investigated, targeting the fabrication of a functionalized composite that is able to detect stress or strain changes in engineering members. Experimental work revealed that internal stresses can be detected based on monitoring the change in resistance as a response to strain. Measurements across sample thickness were found to be most suitable for making general statements about the resistivity of the samples. Hereby, the resistance depends on the intrinsic and the process specific properties of the material. The printing setup was systematically varied in terms of raster angle and gap width. to yield the most sensitive constellation for conductivity The use of a negative gap between the individual rasters in combination with a raster angle of $+/-45^\circ$ was observed to have a positive influence on intensifying the detected signals, making this constellation most sensible for strain sensing applications. Hence, the intrinsic properties of material were enhanced by the adequate selection of processing parameters. This study shows that the functionalized composite can be used as a strain sensor as for health monitoring purposes, to give an example.

1. Introduction

Polymer matrix composites are widely spread owing to their lightweight and high specific properties that can be easily tailored to the requested application. During the lifetime of the structural member, it is of vital importance to monitor the internal strains, associated stresses or vibrations within the structure to give information about the performance of the entire system [1–4]. Further, health-monitoring systems adopt the economic approach not to substitute a part unless it is no longer able to fulfil its function. The detection of failures is commonly achieved using non-destructive testing methods such as ultrasound or X-ray imaging methods. However, these are often difficult to apply to a structural member during its service life.

Another way for crack detection is based on the use of functional materials, where an electrically conductive filler is introduced to the polymeric matrix. The electrical resistance of the structure, measured by means of external sensors, provides knowledge about internal stresses, and can thus allow online crack detection. Common fillers are Carbon Nano-Tubes (CNT) [2,5–9], Carbon Fibres [1,10–16], Graphene [8,17,18], Graphite [19,20], and Carbon Black (CB) [2,18,21,22]. Due to the nature of conductivity through the polymeric structure, any change in shape of the conductive network, as a response to deformation or loading, would result in an immediate change in resistance.

Literature reports two mechanisms for conductivity in such polymer matrix composites. As illustrated in Fig. 1, percolation is based on the existence of touching filler material, forming a conductive network that allows the transfer of electrons. Tunnelling, on the other hand, occurs between discontinuous conductive fillers having a very thin polymer film in between (in the range of nm) through which electrons can penetrate allowing conduction to occur [23–31]. The electrical resistance, in this case, depends on the polymeric material and film thickness separating the two neighbouring but non-touching conductive particles. In contrast to first perceptions assuming higher electrical conductivity in case of percolation, recent studies have proven that the incorporation of conductive fillers of large aspect ratio (as in case of graphite) can achieve higher overall electrical conductivity through the polymers by tunnelling mechanisms. In practice, both mechanisms often simultaneously take place within conducting polymer composites, where according to internal structure the one or the other may prevail.

Next to the functionalization of polymers for strain sensing purposes through the addition of conductive fillers, further tailoring for the required application can be achieved through the optimisation of 3D printing parameters during manufacturing. Here, a 3D computer-based CAD model of the part to be manufactured is prepared, which is then sliced into multiple layers of predefined thickness. Finally, suitable equipment produce the part by stacking the thin layers of material in

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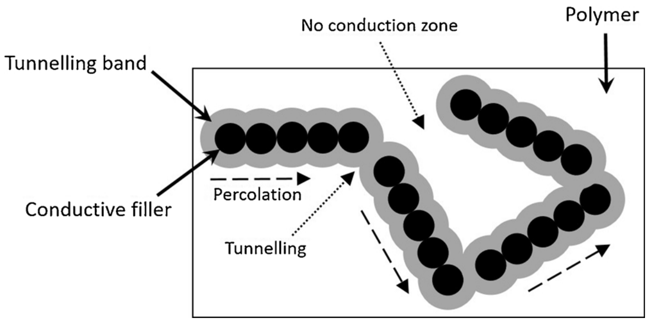

Fig. 1. Tunnelling and percolation conduction mechanisms.

accordance to the sliced area. One of the most spread techniques is Fused Deposition Modeling (FDM) in which thin filaments of material are molten and extruded through a thin nozzle to deposit the individual layers. Studies [32–38] have shown that the variation of printing parameters such as printing speed, layer thickness, gap width and scaffolding angle plays a major role in determining the mechanical and physical behaviour of 3D printing parts.

Although initially designed for the rapid fabrication of scale models and prototypes, developments over the years were dedicated to new techniques, materials and of course enhanced efficiency and productivity. This has led to the advancement of the concept to reach rapid tooling as well as rapid manufacturing. With these targets, not only shape and contour but moreover functionality and performance are becoming crucial aspects [6,10,18,21,22]. Next to the development of metallic and ceramic materials, a number of new polymers have been introduced: Polylactic Acid (PLA) as a stiff and environmentally-friendly material, Nylon for soft applications (e.g. bracelets), high density polyethylene (HDPE) for the production of food-compatible parts and Acrylonitrile Butadiene Styrene (ABS) as a general solution for tough parts with acceptable strength.

The use of rapid prototyping techniques for the manufacture of conductive, lightweight, and functional parts has been sufficiently discussed in literature. However, the influence of printing parameters such as the raster angle and the air gap between two successive rasters must not be underestimated. Therefore, this study is dedicated towards the investigation of the effect of such parameters on the change in relative resistance of Carbon Black filled ABS printed parts under tensile loading.

2. Experimental work

2.1. Materials

Carbon Black filled ABS filament was supplied by Grand Kevan Industrial Co. Ltd for the preparation of 3D printed parts. Thermogravimetric analysis according to [21,39], using a TA Instruments Q50 Thermogravimetric analyser revealed a filler content of 26.37%. Density, determined according to the Archimedean principle on an Adam Equipment PW254 sensitive scale, was found to lie at 1.11 g/cm^3.

2.2. Sample preparation

FDM samples were produced using a DIY FDM machine of 280 × 380 × 120 mm print volume, running on a Marlin firmware that communicates with the user interface software Repitier-Host version V1.0.4 obtained from Hot-World GmbH & Co. KG. STL files were generated using Solid Works 2012 CAD software and further sliced for printing using Slic3r program version 1.1.7.

FDM dog-bone tensile specimens were printed in compliance to ISO standard 527-2 sample type 1BA. To prevent variation in FDM sample properties due to temperature differences in build volume, each sample was printed individually on the central bed region according to the machine parameters given in Table 1. The scaffolding angle and the air gap between rasters was further varied as summarized in Table 2. These printing parameters cover the common range of applied parameters during FDM as mentioned in [36,40–43]. Further details about the effect of these processing parameters on the mechanical and tribological properties are provided in [37] and [38], respectively.

Table 1
FDM printing parameters.

Parameter	Value
Nozzle diameter	1 mm
Layer thickness	0.5 mm
No. of contours	1
Printing speed	30 mm/s
Nozzle temperature	250 °C ± 5
Bed temperature	120 °C ± 5

2.3. Characterization methods

Electrical resistance was measured using the experimental setup illustrated in Fig. 2a. Here a tensile specimen (illustrated in Fig. 2b) was loaded up to fracture in compliance to DIN EN ISO 527-2 using a Lloyd LRX Plus Universal Testing Machine equipped with a 2.5 kN load cell at a crosshead speed of 2 mm/min. The electrical resistance of the samples was measured in-line during loading using a UniT UT61B multimeter, connected to a computer for data acquisition, at a sampling rate of 1/s. In order to enhance the conductivity between the multimeter alligator probes and the sample, SEM grade conductive carbon tape was applied under the alligator tips as depicted in Fig. 2b.

Following the literature [11–13,15,16,18], three contact alternatives between the sample and the multimeter probes were studied for each layup, as given in Table 2. The position of these probes on the sample body was varied to study the conductivity through even layers, odd layers and across the thickness, indicated as measurements between points A–B, C–D or A–D, respectively, as labelled in Fig. 2c.

3. Results and discussion

Fig. 3 shows a general photograph of the printed tensile samples considered for the analysis, in addition to its fracture surface. The illustrated SEM image shows the well dispersed distributed carbon black particles of 84 nm size, and their networking action to form a conductive structure.

Fig. 4 displays the mechanical and electrical response of a -P0 layup loaded under tension up to fracture and examined for conductivity through the surface (-M0). The presented behaviour is typical for all FDM samples under investigation. The stress-strain behaviour showed elastic deformation followed by brittle fracture terminating the tensile test. This may be attributed to the high filler content that prohibits the reorientation and slippage of polymer chains, thus preventing the typical plastic deformation of polymers. The change in stress as a response to sample straining was accompanied by a change in conductivity, which was recorded in terms of relative resistance (change in resistance with respect to resistance at test start). The change in relative resistance was observed to follow an exponential trend. This behaviour is not only typical for conductive polymers, but is also characteristic for each type of conductive filler [1–3].

The detailed view of test beginning (illustrated in the upper corner of Fig. 4) shows that the relative resistance droped to −0.2% upon loading, after which it started to continuously increase until sample failure. This can be explained in view of the two conducting mechanisms simultaneously taking place within the polymer composite. When strain is applied, the conductive network is broken at some points (isolation), whereas new network nodes of conduction are created at