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A comparison between mechanical properties of specimens 3D printed with virgin and recycled PLA

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Abstract

The current research was focused on a further insight into the mechanical properties of 3D parts printed with virgin and recycled polylactic acid (PLA). A first set of specimens was printed with virgin PLA filament and mechanically tested. Such specimens were then ground up and re-extruded into filament using a homemade extruder. The re-extruded filament was employed to manufacture a new set of specimens which were also analysed. Three recycling processes were performed to assess the effect on the mechanical properties. The obtained results suggested that 3D printing with recycled PLA may be a viable option.

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Keywords: Additive Manufacturing; Mechanical properties; Recycled polymers

1. Introduction

Over the past few years additive manufacturing has been growing rapidly. This technology allows for a quick and inexpensive production of devices without machining or tooling. Furthermore, the important role of computer-aided design (CAD), reverse engineering and theoretical/experimental analyses has been frequently stressed the literature [1-12] as the use of such methodologies has led to the design of advanced devices for different applications [13-20]. Due to an improvement in the additive manufacturing technologies and production speeds, it seems that the amount of 3D printed polymers will continue to increase. Considering the mass production abilities, it is well known that 3D printing is characterised by a volume which will never approach that of an injection molding process. Anyway, today additive manufacturing (i.e.,3D printing) allows for the production of a great number of parts with specific shapes (i.e., up to 5000) also at competitive costs, even if fused deposition modelling (FDM) is generally considered for small production runs and prototypes which are not "functional" parts or devices [21-26].

However, a significant amount of waste is still created by FDM such as failed prints and support structures, disposable prototypes and many iterations. In this context, many materials such as polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) are employed as printing materials. PLA is a biodegradable polymer coming from plant materials (i.e., corn starch and sugar cane). Moreover, scrap PLA may be managed using different methods, such as recycling, combustion, composting, and dumping in landfills [26]. Concerning the environmental impact, recycling is by far the best method to manage scrap PLA, whereas composting is not considered a realistic solution as a consequence of the full degradation time and particular process conditions. On the other hand, in terms of environmental efficiency, the production of carbon dioxide clearly limits the combustion method. As reported in preliminary studies, with regard to the

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environmental impact, PLA recycling results 16 and 50 times better than combustion and composting, respectively [26-28].

If compared to petroleum-based plastics, PLA has a less environmental impact [26,29]. For this reason, many kinds of recycled filaments, which are obtained processing waste using filament extrusion systems, are currently available in the market. To potentially save over thousand million MJ of energy per year and to reduce greenhouse gases, "distributive recycling" has been conceptually considered instead of "centralised recycling" [26,30].

Even though many advances and interesting technical features have been reported in this field, little is known about the mechanical properties of virgin and recycled 3D printed polymers [26,31,32]. Specifically, it has been proved that the use of a filament recycled twenty times through an extrusion-based process minimally affected the tensile strength and modulus of PLA [26,33]. In addition, a study on recycled polypropylene blends in injection moulding procedure was performed and an appropriate blending ratio of virgin and recycled polymer was assessed, showing that the decrease in the mechanical properties of devices fabricated from recycled polymers may be improved optimizing the process parameters during the injection moulding [26,34,35].The influence of regrind on the properties of polymer processing by injection moulding was properly evaluated [26,35]. A study focused on optimization methods and strategies related to additive manufacturing and a filament, which was recycled five times and then employed for the fabrication of a 3D printed component, demonstrated no decrease of mechanical properties other than a reduction of 10% in the tensile strain at break [26,36]. A previous research was already focused on the mechanical performances (i.e., tensile, shear, and hardness properties) of 3D specimens printed using both virgin and recycled PLA [26]. Briefly, PLA specimens were printed and re-extruded into filaments. Further specimens were printed with recycled PLA filament and then mechanically tested [26]. The obtained results showed that 3D printing and recycled PLA may be considered a valuable option as the recycling process did not dramatically alter the mechanical properties and the tensile elastic modulus was not significantly changed [26].

Accordingly, the current research was focused on a further insight into the mechanical properties and a comparison of specimens 3D printed with virgin and recycled PLA through the evaluation of the interlaminar properties and short-beam strength.

2. Materials and methods

Short-beam strength specimens were fabricated according to the ASTM D2344 in order to analyse the interlaminar properties and short-beam strength.
The PLA specimens were manufactured at 200°C using a 3D printer (Prusa I3) and 0.4 mm nozzle.
A first set of specimens was printed with virgin PLA filament and mechanically tested. Such specimens were then ground up and re-extruded into (1.75 mm) filament using a homemade extruder (Fig. 1).

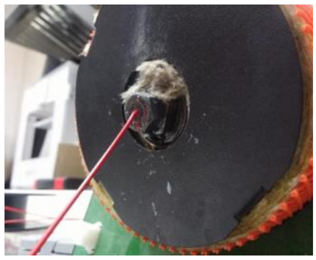

Fig. 1. An image of the filament extrusion.

The re-extruded filament was employed to manufacture a new set of specimens which were also analysed. Specifically, three recycling processes were performed to assess the effect on the mechanical properties.
Mechanical tests for short-beam strength (ASTM D2344) were performed on specimens 3D printed with virgin and recycled PLA. A span length-to-specimen thickness ratio of 4.0 was used.
Test specimens were loaded in three-point bending. They were centre-loaded and the ends rested on two supports which allowed lateral motion. The loading nose was directly centered on the midpoint of the specimen (Fig. 2).
The short-beam strength (F^{sbs}), which is generally defined as the shear stress developed at the specimen mid-plane at the failure event, was calculated according to the following equation:

$$F^{sbs} = 0.75 \times \frac{P_m}{b \times h} \quad (1)$$

where P_m represents the maximum load measured during the test, whereas b and h are the specimen width and thickness, respectively.

3. Results and discussion

The short-beam strength was evaluated from mechanical tests performed on 3D specimens printed with virgin and recycled PLA, and reported as mean value ± standard deviation (Table 1).

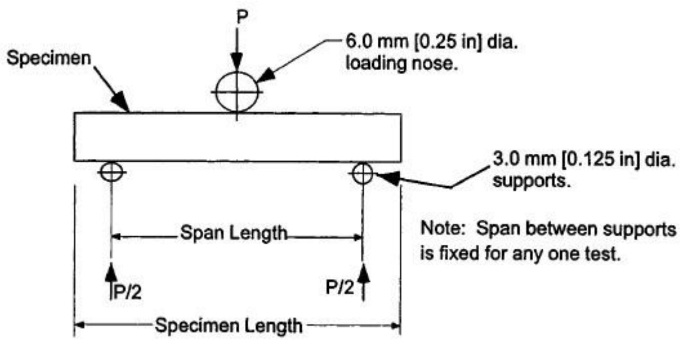

Fig. 2. Schematic representation of the experimental setup – horizontal shear load diagram (adapted from ASTM D2344).

Table 1. Results from mechanical tests: short-beam strength reported as mean value ± standard deviation.

PLA filament	Short-beam strength (MPa)
Virgin	119.1 ± 6.6
One time-recycled	106.8 ± 9.0
Twice recycled	108.5 ± 9.9
Three times recycled	75.0 ± 16.2

Typical images obtained from mechanical tests are reported in Fig. 3.

As frequently reported, the ASTM D2344 three-point bending test method is generally employed to determine the short-beam strength of high-modulus fiber-reinforced composite materials. It is limited to discontinuous or continuous-fiber-reinforced polymer matrix composites with balanced and symmetric elastic properties with respect to the longitudinal axis of the specimen. Even though a variety of failure modes may occur as internal stresses are complex, shear is considered to be the dominant applied loading using such test method. In addition, taking into account the stress state local to the loading nose, it is also worth remembering that failure may initiate as a consequence of a combination of a severe shear stress concentration with in-plane and transverse and compressive stresses. Anyway, in the case of more ductile matrices, the situation under the loading nose may be alleviated by the plastic yielding, and other failure modes may occur (i.e., bottom surface fibre tension). Consequently, unless mid-plane interlaminar failure can be clearly noticed, the short-beam strength assessed through this test method cannot be ascribed to a shear property, and the reported Equation 1 will be unable to yield accurate values for the shear strength.

However, as FDM process is based on a layer by layer material deposition method, the employed test method was used to assess the interlaminar properties and short-beam strength.

A previous work [26] already demonstrated the possibility to produce filaments with usable properties even if some difficulties generally arise from working with recycled filaments. In particular, Anderson (2017) [26] compared virgin and recycled formats in terms of hardness, tensile and shear properties, and demonstrated that devices with appropriate mechanical properties may be manufactured with filament recycled from previously 3D printed parts.

For this reason, the current research may be considered a further insight into the mechanical properties of 3D specimens printed with recycled PLA and should provide interesting information in terms of recycling process in the field of 3D printing.

Fig. 3. Results from mechanical tests: typical failure modes.

Taking into consideration the obtained results, it is worth noting that the use of one-time and twice recycled filaments did not significantly affect the short-beam strength, which dramatically decreased after a further recycling process (Table 1). The results obtained from the three times recycled filament showed an increased standard deviation and, hence, a great variability (Table 1). Specifically, the decrease in the values of the short-beam strength as well as the great variability could be ascribed to different factors (i.e., potential degradation phenomena of the filament, flow behaviour and rheological properties) and could be properly avoided through the optimization of the printing and recycling process.

4. Conclusion

A previous research already evidenced the possibility to save great amounts of raw materials, energy cost, and CO_2 emissions in the fabrication of 3D printed devices.

The current research represents a further insight into the mechanical properties of specimens printed with recycled PLA, especially focusing on interlaminar properties and short-beam strength. The recycled PLA filament was employed to manufacture 3D printed specimens and mechanical tests for short-beam strength were performed. The one-time and twice recycled specimens showed a short-beam strength (106.8 ± 9.0 MPa and 108.5 ± 9.9 MPa, respectively) which was similar to that of the virgin specimens (119.1 ± 6.6 MPa). However, a third recycling process negatively affected the values of the short-beam strength also producing a great variability in the results (75.0 ± 16.2 MPa).

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