Effect of Filament Storage Conditions on the Mechanical Properties of 3D Printed Objects Prepared with Fused Filament Fabrication

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***Abstract*—In this current study, the relations between the mechanical properties of 3D printed objects and the humidity of the build material during the 3D printing process have been investigated. For this purpose specimens were prepared from poly(lactic acid) (PLA) using the fused filament fabrication technique. The PLA filament used as building material was stored in a humidification chamber before and during the 3D printing process. The relative humidity (RH) in the chamber was varied in the range of 10-90%. A total of five sets of specimens were prepared at 10%, 30%, 50%, 70% and 90% RH. Mechanical properties of the fabricated samples were determined by means of tensile tests and Charpy impact tests. According to the results, the specimens printed from the filaments stored at 10% RH exhibited the highest tensile strength (~55 MPa), Young's modulus (~2.7 GPa), elongation at break (~2.6%) and impact strength (~17.6 kJ/m^2) values. The higher RH values generally resulted in lower mechanical properties, bottoming at 90% RH, at which point all the properties suffered a relative loss of 10-15% compared to the samples prepared at 10% RH.**

Keywords—fused filament fabrication, poly(lactic acid), 3D printing, humidity, mechanical properties

I. INTRODUCTION

In the recent years, additive manufacturing – also referred to as 3D printing – techniques have seen an immense development, while also receiving an increasing attention worldwide [1]. These novel manufacturing techniques have been widely used in various fields, including the aerospace, biomedical, architectural and vehicle industry [2-4]. Additive techniques are based on the principle of building products through a layer-by-layer process and offer numerous advantages, including reduced production time and production costs. There is also the possibility to fabricate complex-shaped objects that would be otherwise impossible or extremely difficult [5-7]. The additive manufacturing processes are generally classified based on the characteristics of the applied building materials. Accordingly, there are three groups of 3D printing processes, namely the solid-based ones, the liquid-based ones and the powder-based ones. The most diffused additive manufacturing method is the so-called fused deposition modeling (FDM) [8], which is also widely known as fused filament fabrication (FFF). Even though their working principle is the same, some authors distinguish the FDM and the FFF machines depending on whether the whole build chamber is being heated (FDM) or only the build platform (FFF) [9, 10]. The FDM/FFF type machines are solid-based 3D printers, they are mostly fed by various thermoplastic polymers, the most common of which is the poly(lactic acid) (PLA) [11, 12].

PLA is a semi-crystalline thermoplastic biopolyester that is produced by the fermentation of starch-rich plants, such as corn, sugarcane, beet sugar and potato [13]. It exhibits decent mechanical properties (high strength and modulus), comparable to that of most petrol-based polymers, good optical properties and it is also biodegradable [14, 15]. On the other hand, it has poor toughness and it is also well-known for being thermally unstable [16]. This latter disadvantage manifests in PLA exhibiting a considerable loss in molecular weight at the temperature range of melt processing. There are several mechanisms being responsible for this, including the chain scission, depolymerization, oxidative degradation, intermolecular and intramolecular transesterification and hydrolysis [17]. Several authors reported [18, 19] that the rate of degradation greatly depends on the moisture content of PLA. Accordingly, the environmental conditions during melt processing are of high importance when it comes to the molecular weight of PLA. Since the molecular weight greatly affects the mechanical parameters of the polymers, this also means that the storage conditions of the building material can significantly influence the properties of the manufactured products [20]. Therefore, under industrial conditions, PLA is always dehumidified in order to avoid degradation prior to melt processing. Individual 3D printing users, on the other hand, mostly neglect this aspect, even though there are commercially available filament dryers these days. These are mostly heated chambers, whose sole purpose is to evaporate the inherent moisture from the filaments. It has to be noted, however, that the effectiveness of these dryers is doubtful, since the temperature resistance of the PLA filaments is generally limited at max. ~55 °C. Accordingly, the ambient relative humidity (RH) is a factor that can greatly affect the

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load-bearing capacity of 3D printed products and therefore, it is something that needs to be calculated with.

In this present study, PLA was used as building material to prepare specimens with FFF/FDM-based 3D printing technique. The applied PLA filaments were stored under various RH conditions prior to and during the 3D printing process. In order to evaluate the effect of humidity on the mechanical properties of the printed objects, tensile tests and Charpy impact tests were performed on the fabricated specimens.

II. Materials and Methods

A. Materials

The polymer used for this study was an "Extrafill Traffic White" grade PLA filament obtained from Fillamentum Manufacturing Czech s.r.o. (Hulín, Czech Republic) with a nominal diameter of 1.75±0.05 mm. According to the manufacturer, this filament is especially sensitive to moisture during the printing process, since it leads to decreased mechanical properties, embrittlement and to stringing (fine strands of polymer occurring when moving the nozzle) during the printing process.

B. Specimen Preparation

The PLA filament was conditioned in an ACS DY110 type humidification chamber (Angelantoni Test Technologies, Massa Martana, Italy) at 50 °C. The relative humidity values were varied for the different sets of samples (10%, 30%, 50%, 70% and 90% RH). Each time, the PLA filament was conditioned for at least 24 hours at the specified temperature and relative humidity values prior to and during the 3D printing process. The specimens for the tests were fabricated using a Craftbot Plus desktop FFF 3D printer (CraftUnique Ltd., Budapest, Hungary). The conditioned PLA filaments were directly fed from the humidification chamber into the printer head through a silicon tube in order for the ambient temperature and humidity not to interfere with the results. The diameter of the selected brass nozzle was 0.4 mm. Throughout the printing process, the nozzle temperature was set to 215 °C, while the platform was heated to 60 °C. The applied printing speed was 60 mm/min and the layer thickness was 0.2 mm. The infill density was set to 100%. Two shell perimeters of 0.4 mm width were used. The specimens were printed horizontally using a unidirectional linear infill with a raster angle of 0° (the infill was parallel to the length of the specimens). The schematic graphic of the prepared specimens and the applied infill pattern are shown in Fig. 1. G-codes were generated using the CraftWare slicer software (1.23 version).

Fig. 1. Schematic graphic of the fabricated specimen geometries and the applied printing pattern

C. Characterization and Testing

The tensile mechanical properties were determined using an Instron® 5582 type universal testing machine (Instron, Norwood, USA) equipped with a 10 kN force sensor. 3D printed dumbbell-shaped specimens with a cross-section of 10 mm × 4 mm were used for the measurement. The gripped length was 100 mm. The tests were carried out at a crosshead travel speed of 5 mm/min. The reported results are the averages of five parallel measurements.

The Charpy impact toughness was determined using unnotched specimens. For this purpose, a Ceast 6545 (Ceast, Pianezza, Italy) testing machine was applied with a hammer of 2 J. The specimens were rectangular bars of 10 mm × 4 mm × 80 mm size. The bearing distance was 62 mm. The reported results are the averages of five parallel measurements.

III. Results and Discussion

A. Tensile mechanical properties

The tensile mechanical properties of the PLA specimens fabricated at various RH values are depicted in Fig. 2-4. Since PLA generally shows a brittle behavior, no yield point was observed on the stress-strain curves and the failure of the tensile specimens occurred at the maximum stress. Fig. 2. presents the ultimate tensile strength of the samples as a function of RH within the humidification chamber, where the filament was stored before/during the printing process. Apparently, the specimens printed at the lowest RH (10%) exhibited the highest strength, 55±3 MPa, which is comparable to those values reported for PLA samples prepared by industrial techniques (i.e. injection molding, extrusion, compression molding) [21, 22]. With increasing humidity, the tensile strength values continuously decreased, bottoming at 47±2 MPa, when the RH was set to 90%. This loss in strength is attributed to the degradation caused by the moisture that the

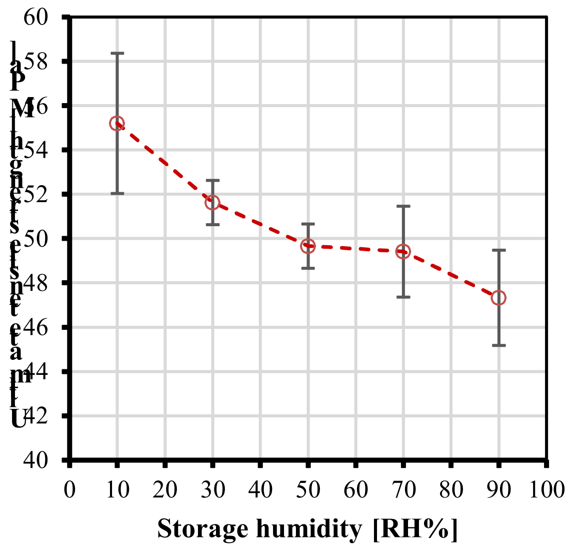

Fig. 2. The effect of storage humidity on the Young's modulus of the printed specimens

filaments absorbed at high RH in the storage chamber. Similar decrease in the strength of PLA was reported in the literature for extrusion melt processing [18]. As a result of degradation, the average molecular weight of PLA presumably decreased. The lower molecular weight values of polymers generally come with poorer mechanical properties, including the ultimate tensile strength. The foremost explanation for this is the fact that with lower molecular weight the individual chain molecules – loosely bonded by weak secondary chemical bonds – can move more easily when being exposed to mechanical stress. On the contrary, the chain molecules of higher molecular weight polymers get entangled and in order to break these entangled chains, more energy is required.

Fig. 3. shows the Young's modulus of the prepared samples. According to the results, the stiffness of the samples also highly depended on the storage conditions of the building material. Similarly to the ultimate tensile strength, the highest Young's modulus was measured on the specimens printed at 10% RH (2.70±0.06 GPa), while it was the lowest when printed at 90% RH (2.39±0.14 GPa). This relative loss of ~12% in modulus can also be attributed to the lower molecular weight, since it requires a lower energy level to loosen the bonds between the less entangled polymer chains for shorter molecules.

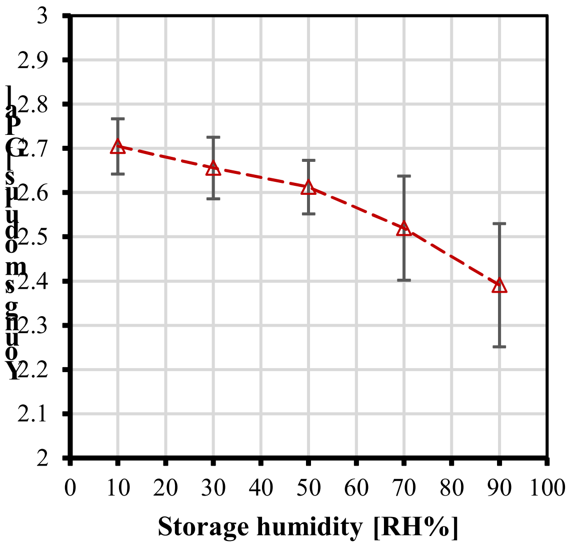

Fig. 3. The effect of storage humidity on the Young's modulus of the printed specimens

The elongation at break values of the samples as a function of RH are shown in Fig. 4. The highest elongation at break (2.57±0.14%) was measured, when the specimens were printed using the lowest RH setting in the humidification chamber (10%). Above this humidity level the deformability of the 3D printed samples dropped to ~2.35% and it remained roughly the same in the examined range of RH, the determined values were all within deviation range. These results are in good accordance with the strength and Young's modulus values and also suggest a considerable degradation as a consequence of increased moisture content. The higher average molecular weight enables the polymer a higher degree of stretching before the rupture, since the higher degree of entanglement allows the material to be pulled further before the individual chains break. This explains why the elongation values peaked at the lowest RH setting.

B. Impact toughness

The impact strength of the prepared samples are shown in Fig. 5. The obtained results of Charpy tests showed that the change in humidity conditions during the storage caused considerable changes in the brittleness of the 3D printed PLA specimens as well. A tendency similar to the tensile test results was observed, namely a decreasing impact strength with increasing humidity level in the storage chamber. Evidently, the degradation caused by the higher moisture content led to an embrittlement of the PLA building material. The impact strength of the fabricated samples showed a maximum (17.6±0.9 kJ/m^2) when the filament was maintained at the

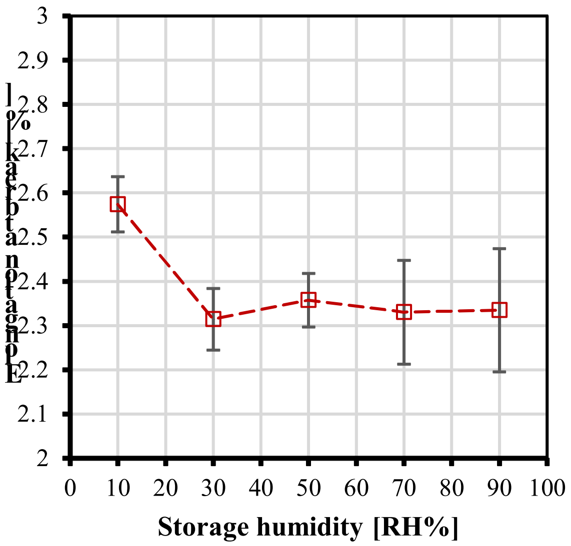

Fig. 4. The effect of storage humidity on the elongation at break of the printed specimens

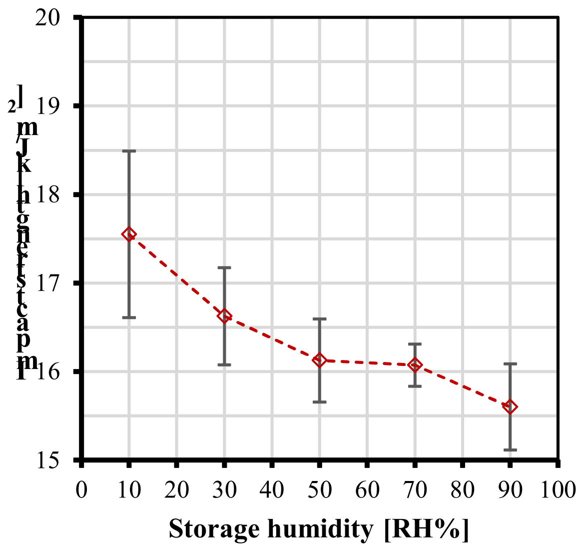

Fig. 5. The effect of storage humidity on the impact strength of the printed specimens

driest conditions. Accordingly, the less degradation (the higher molecular weight) came with a higher impact resistance of the material. This can be attributed to the fact that more bonds need to be broken before the failure, which means a higher energy absorption – a higher impact resistance - until the specimen ruptures.

IV. Conclusions

Relationships between the mechanical properties of 3D printed objects and the humidity of the build material before/during the 3D printing process have been investigated. The applied 3D printing technique was FFF, while the build material was PLA. Mechanical properties have been assessed based on tensile tests and Charpy impact tests. According to the results, with increasing humidity the moisture content of the PLA filament gradually increases that leads to immense degradation during the melt processing. This phenomenon manifested in the decrease of ultimate tensile strength, Young's modulus, elongation at break and impact strength properties. The mechanical properties of the samples prepared with the filament being conditioned at lowest humidity (10%) outperformed the ones conditioned at 90% RH relatively by 10-15% in all aspects.

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