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IMPACT OF MOISTURE ABSORPTION ON 3D PRINTING NYLON FILAMENT

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Abstract

Nylon is a commonly used thermoplastic material featured for its high resistance to heat, chemical, and impact. Nylon filaments that facilitate complex part manufacturing through the extrusion-based 3D printing process are widely used in industry and can be easily acquired from various vendors or suppliers. However, as a hygroscopic material, nylon directly absorbs moisture from the surrounding air at a fast rate. This study concentrates on evaluating the moisture absorption of nylon filament in a humid environment. Experiments are conducted to correlate the moisture content of nylon filament with its dwelling time in a humidity chamber. Test artifacts are printed to demonstrate the influence of moisture on nylon part quality. Mechanical testing is also carried out for analyzing the material property degradation due to increased moisture content. Suggestions on nylon filament usage and storage are discussed.

Introduction

As a commonly used thermoplastic material, nylon designates a family of synthetic polymers composed of polyamides of high molecular weight. Nylon polymers are tough, strong, and outstanding for its high resistance to heat, chemical, and impact, which are of great interest for commercial applications. With the introduction of additive manufacturing or 3D printing to the market, nylon becomes a popular feedstock material in the form of powder (for selective laser sintering process) and filament (for fused deposition modeling process). Especially, 3D printing nylon filament affords great convenience for making parts of low-volume production or complex structures, using an extrusion-based 3D printer. Also, nylon filaments are low-cost and easily acquired through various vendors or suppliers, making 3D printing for nylon parts very accessible to end users.

The influence of moisture on 3D printing is of great interest in a wide range of areas. Many commonly used 3D printing filaments, such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polycarbonate, or related composites, were studied revealing how the material properties are changed and how the impact of moisture is addressed [1-4]. Some 3D printing filaments for pharmaceutical application were investigated for stability challenges of varied storage conditions including temperature and relative humidity [5]. Shrinkage behavior of building materials for 3D printing was also studied regarding the different drying or moistening conditions [6]. As a hygroscopic material, nylon plastic can absorb moisture from surrounding humidity. Monson et al [7] reported the dimensional changes associated with moisture absorption of various polyamides. Banjo et al [8] 3D printed nylon specimens and immersed in deionized water at different temperature and concluded that nylon-based materials absorb much more water than 3D printing PLA specimens. A direct relationship between moisture absorption and reduction in flexural properties was also observed for the nylon specimens. The degradation of nylon material can be attributed to the amount of filament moisture, which acts as a plasticizer reducing the molecular entanglements and bonding between the molecules [9]. It has been found that water sorption (immersion into liquid water bath) has very different transport mechanism at surface compared to the moisture sorption (moisture in air) [10]. Thus, this project extends to study the effects of humidity on the feedstock filament of nylon materials in the 3D printing process. The characteristics of 3D printed nylon specimens are evaluated at various moistening time (moisture contents) to reveal the influence.

Experiment

The feedstock material *OVERTURE Easy Nylon filament* (1.75 mm) was acquired for this study. The virgin filament was placed in a *MEMMERT* humidity chamber for absorbing moisture. The humidity chamber was set with a constant temperature (40 °C) and humidity (80 % rh) to mimic a stable humid environment. After a certain amount of time, the moisture content of the nylon filament was measured using a *Torbal* moisture analyzer (model no. BTS110). The nylon filament was then fed into an extrusion-based *CreatBot* F430 3D printer for printing specimens. Three types of nylon artifacts were created for comparison of varied moisture content: extruded material, thin-wall samples, and tensile testing specimens. The extruded material is the continuous nylon fiber being pushed out of the nozzle. The thin-wall sample has a hollow cubical shape with a wall of stacked nylon strand. The size of the tensile testing specimens is in compliance with the ASTM D638 standard (tensile testing for plastics), with a thickness 4 mm. The tensile specimens are printed with a *YZ* orientation, as per ISO/ASTM 52921 standard. The extruded materials and thin-wall samples were observed using an *Olympus* optical microscope (BX53M) and a *Keyence* 3D Measurement Macroscope (VR-3200). Tensile specimens were tested using a MTS Criterion™ Model 43 tensile tester at room temperature. The experimental procedure of moistening and 3D printing is illustrated in Fig. 1.

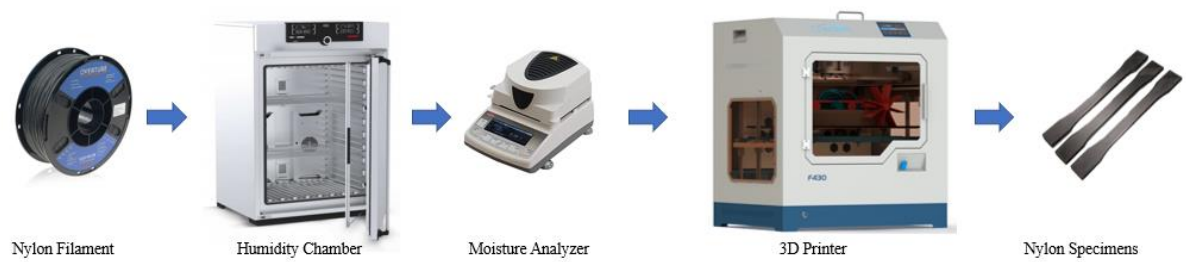

Fig. 1 Experimental set up

Results and Discussion

Moisture measurement

As a hygroscopic material, nylon directly absorbs moisture from the surrounding air at a fast rate. In this study, nylon filament was placed in the humidity chamber by varying the dwelling time at four levels (0*h*, 24*h*, 48*h*, and 72*h*). Time=0*h* represents virgin filament without any moistening. The measured moisture content of nylon filament is shown below in Fig. 2.

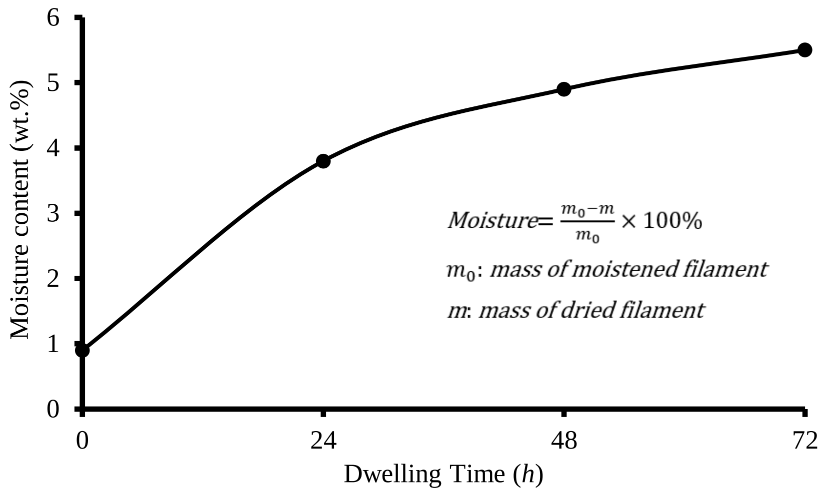

Fig. 2 Moisture versus dwelling time of nylon filament in the humidity chamber

The plotted curve in Fig. 2 exhibits a dramatic increase in moisture content with the extended dwelling time. It is noted that even the virgin nylon filament (0*h*) contains about 1 wt.% water, which is ascribed to the moisture absorption during the filament production. The hygroscopicity of nylon material causes an inevitable moisture absorption when a package of nylon filament is installed for an extrusion-based 3D printer, especially for a printer without full enclosure. When the environmental humidity reaches to a high level, the nylon filament continuously absorbs the moisture in the air. This can be demonstrated by the moisture curve illustrated in Fig. 2. It can be seen that, in a warm and humid environment (40 °C and 80% rh), the moisture content of nylon filament is proportional to the dwelling time. The moisture of nylon filament is measured to be around 5.5 wt.% after being placed in the humidity chamber for three days (72*h*), showing no sign of saturation. The nylon filament exhibits comparable absorption rate to the nylon samples immersed in deionized water (Ref [8]).

Extruded Material

Extrusion-based 3D printing process, such as FDM or FFF, extrudes melted material (like a fiber) in thin strands and bonds to the prior layers or substate. In this study, the extruded material is sampled by collecting the nylon fibers of different moistening time. As shown in Fig. 3, the morphology and consistency of the extruded material are significantly influenced by the moisture content of the feedstock filament. Generally, 0*h* and 24*h* nylon fibers maintain a consistent shape of circular cross-section about 0.4mm in diameter. A few bubbles originated from water evaporation burst after nylon material is extruded out of the nozzle tip. Hence, the defective sites are observable on the surface of the 24*h* nylon fiber. However, if a high moisture content is introduced in the nylon filaments (48*h* and 72*h*), the evaporated water bubbles severely deteriorate the nylon fiber morphology, due to the interior bubble expanding and exterior bubble bursting. The viscosity of melted nylon decreases with the increased moisture uptake, which expedites the void formation or foaming. Also, the formation of hydrogen bonds between water and carbonyl and ether linkages in the polymer chain causes the “pseudo-crosslinking” effect [11], which results in the extruded material degradation. A smooth and straight nylon fiber cannot be achieved. Some expanded big bubble even disrupts the continuous fiber and causes an extrusion inconsistency. The high moisture content is believed to negatively influence the 3D printing parts of nylon filament.

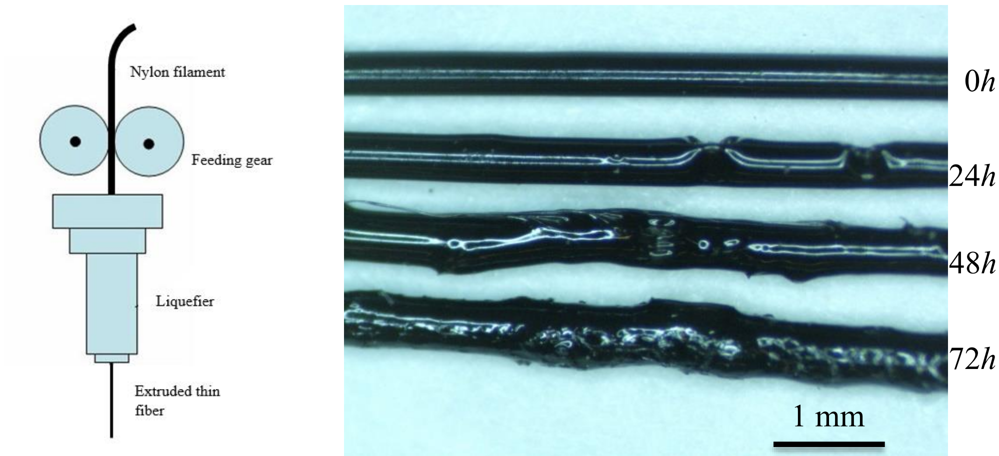

Fig. 3 Schematic of extrusion-based 3D printing process and the extruded nylon materials of different moistening time

Surface finish

Four thin-wall samples were printed using the moistened filaments to reveal the influence of moisture on surface finish of 3D printing nylon part. The lateral wall is characterized using the *Keyence* automatic 3D measuring macroscope. It is found that the surface quality is dramatically decreased, ascribing to the deteriorated nylon strand with a higher moisture. Fig. 4 clearly visualizes the change of surface finish with specific moistening time (or increased moisture content) of nylon filaments.

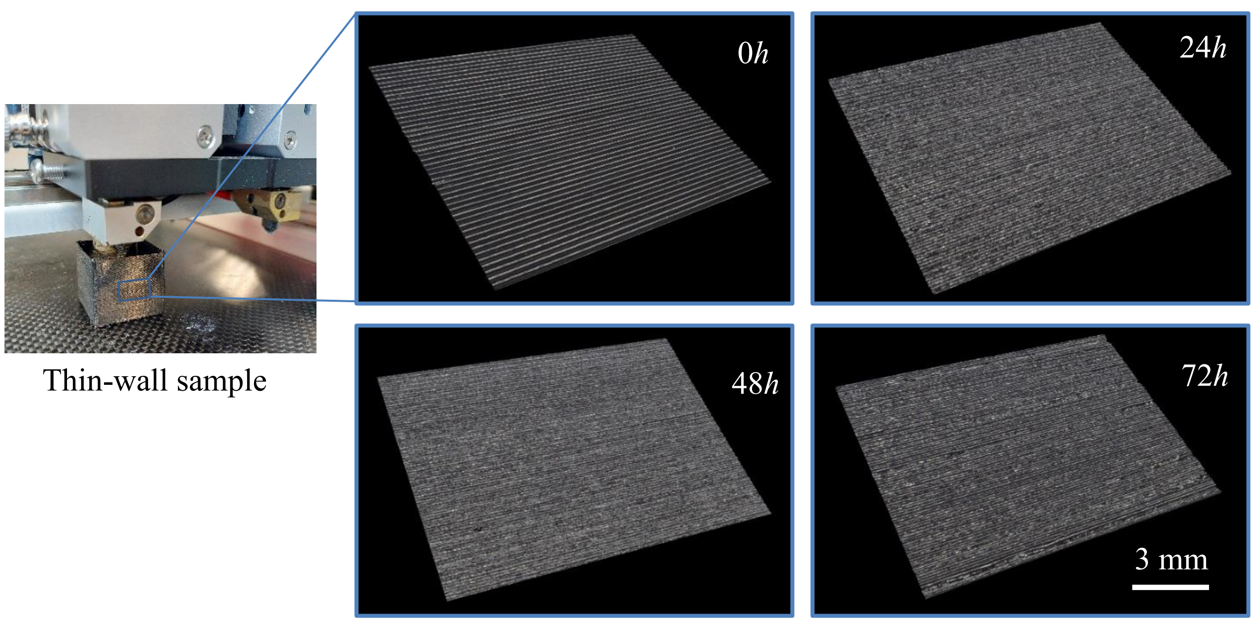

Fig. 4 Lateral surface profile of thin-wall nylon samples

The surface roughness *Ra* was evaluated based on the scanned surface profile. The evaluation length is ~5mm and directed along the building direction (orthogonal to the layers).

Periodic peak and valley can be observed on the roughness profile, as shown in Fig. 5. The *Ra* value is automatically computed through the profile heights over the evaluation length. It is noted that the *Ra* value does not change as much as observed surface finish, even though the roughness profile of 48*h* and 72*h* samples presents apparent irregularity. The influence of moisture on the surface quality of 3D printing nylon parts can be easily disregarded if only *Ra* measurement is conducted. Visual comparison to the nylon surface finish of various moisture contents is usually not achievable if the nylon filament has already been moistened. 3D printing part evaluation is suggested for multiple metrological methodologies to confirm its surface quality.

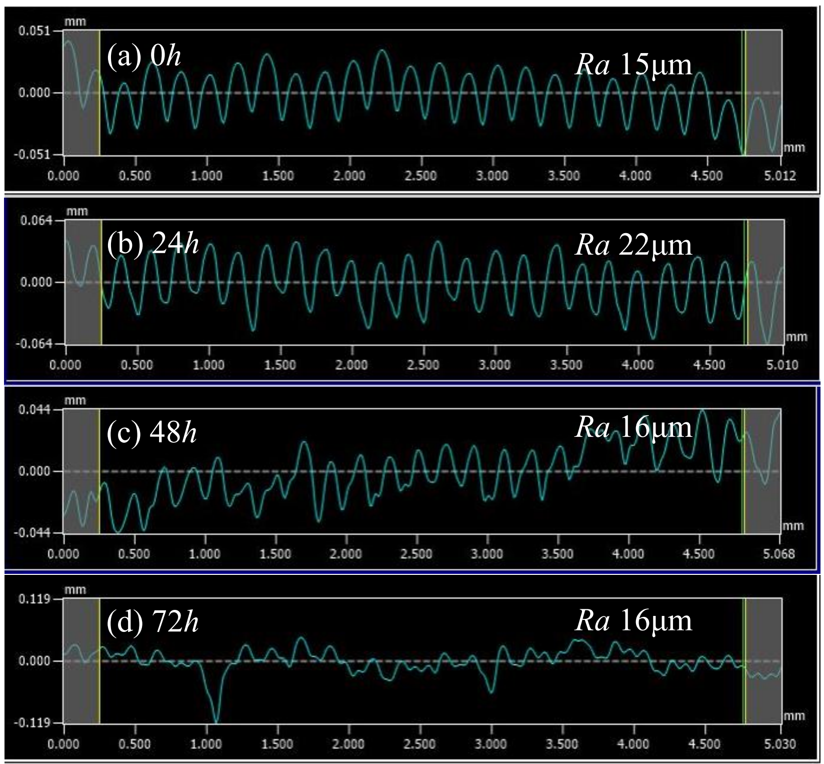

Fig. 5 Roughness profile of nylon thin-wall samples

Mechanical testing

Tensile test was conducted at room temperature to specimens which were 3D printed using the virgin nylon filament (0*h*) and moistened nylon filament (72*h*). The test aimed to demonstrate the effect of moisture content on the tensile strength of nylon materials. Thus, only two types of filaments, with very distinct moisture content (0.9% vs. 5.5%), were adopted. The tensile specimens conform to the ASTM D638 Type I size requirement, with a thickness of 4 mm. Four duplicates were tested for each type of tensile specimen. The stress-strain curve is shown in Fig. 6. 3D printing plastic materials usually present a varied mechanical property. Hence, it is anticipated the slight variation of the tensile curves occurs between 0*h* nylon specimens, such as elastic modulus (1.50~1.81 GPa). It is noted that two 0*h* tensile specimens were not ruptured during the test because the extensometer reached its strain limitation. Two stress-strain curves of 72*h* specimens are completely overlapped. Overall, the nylon specimens which were 3D printed using virgin filament exhibit great elasticity and ductility. However, the tensile properties of the nylon specimens printed using 72*h* moistened filament are clearly degraded, especially in ductility. The max strain value of 72*h* tensile specimens is only 8%, which is significantly lower than the 0*h* specimens. The yield strength and ultimate tensile strength are also lowered due to a high percentage of moisture content. The degraded nylon material of extrusion is believed to contribute to the inferior tensile property. Aforementioned, the void formation and "pseudo-crosslinking" effect cause the extruded nylon material degradation. Moisture acts as a plasticizer and reduces the strength and stiffness of the nylon material. In addition, water molecules diffuse into the nylon structure and bond to the polymer chain within the amorphous regions, forcing the polymer chains apart. This would substantially weaken the layer bonding during 3D printing nylon filaments. Overall, these factors are composited to cause the decreased ductility of nylon specimens printed with filament being exposed in the moisture.

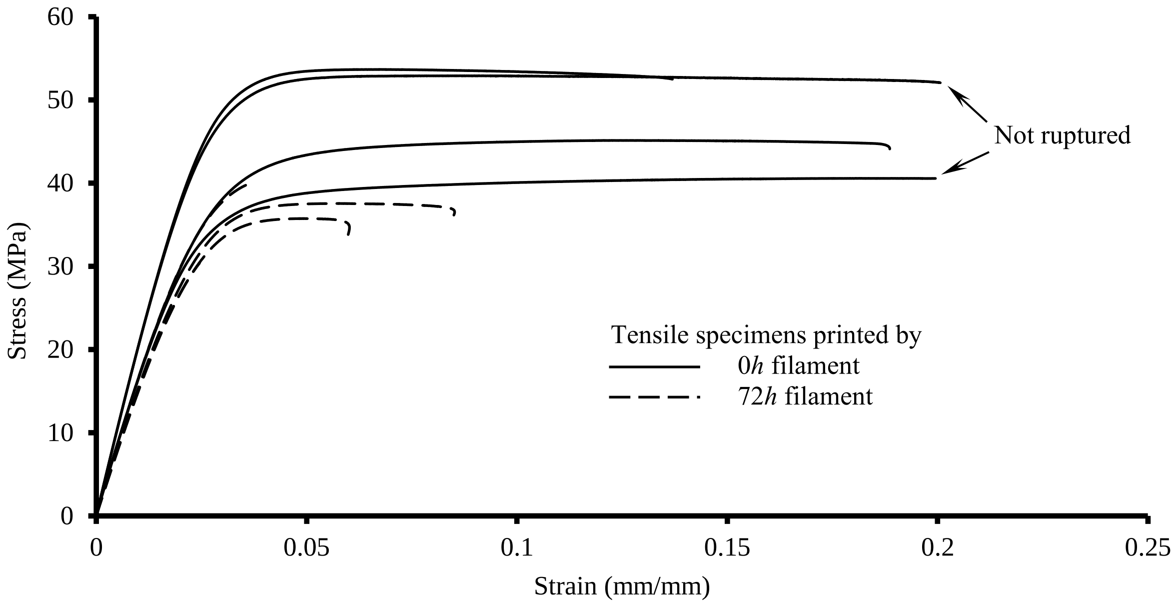

Fig. 6 Stress-strain curve of tensile testing specimens of nylon

The influence of moisture on 3D printing nylon filament, not limited to nylon material, deserves extra attentions, based on the results and discussions of this study. It is noted that the quality of material extrusion, surface finish, and mechanical property are all diminished due to the moisture absorbed by the nylon filament. As a hygroscopic material, the usage and storage of nylon filament must be carefully handled and managed to ensure to the 3D printing part quality. The filament operation guidelines and protocols are suggested to be proposed to avoid the inconsistency of mechanical properties of 3D printing parts. In general, the environmental humidity must be well controlled when using nylon filament for 3D printing. An enclosed chamber is recommended for the printing process. The unused nylon filament should be wrapped in a vacuum condition to avoid contacting moisture in the air. If the filament is out of supervisory monitoring for a long term, the moisture analysis should be conducted to verify its eligibility for quality part. Otherwise, the suitable drying must be performed before reusing the moistened filament.

Conclusion

This study relates the moisture content of 3D printing nylon filament with the dwelling time in a constant humid environment. The moisture measurement confirms the hygroscopicity of nylon filament. The negative influence of moisture on nylon filament is demonstrated through analyzing extruded materials, surface finish, and tensile property of nylon specimens. It is found that the extruded nylon material is significantly degraded if the filament is highly moistened, causing an irregular surface finish as characterized. The tensile property is also lowered, especially for ductility, due to the composited factors of water molecules to the nylon filament. Hence, operation guidelines or standards are desired for handling filaments to ensure a consistent 3D printing part quality.

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