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Filament 3D Printing Technology for Diffuse Optics Applications: Advantages and Drawbacks

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Abstract: PLA and ABS filaments, 3D printed as thin sheets were optically characterized in UV/VIS/NIR. The applicability of these materials, used as optical probes, in diffused optics applications was tested through TD-NIRS and DCS measurements.

1. Introduction

Diffuse Optics (DO) exploits the interaction of VIS/NIR light with turbid media to determine their optical properties, i.e. absorption (μ_a) and reduced scattering (μ'_s) coefficients. DO techniques are widely used in different scenarios: biomedical field (to non-invasively determine the hemodynamic properties of human tissues), agriculture (to non-destructively assess fruit quality), pharmaceutical tablets and wood (e.g. for quality control during production). Light is generally delivered to and recollected from the sample by optical fibers, and custom-designed optical probes, i.e. holders for optical fibers, are often necessary to guarantee good adhesion of the optical fibers to the sample. Fused Deposition Modelling (FDM) technology, and in particular 3D filament printing, is a perfect candidate: it allows to build tailor-designed objects at very low cost and usage simplicity (as compared to other additive manufacturing techniques). Nowadays, there is a lack of information about the optical characteristics of materials employed in FDM printers, and not much information about their usage in DO have been reported. In this work we present an optical characterization of two of the most used materials for filaments: polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). We selected filaments of different colors and producers, and 3D printed them at different temperatures. Moreover, we tested two optical probes, printed with two black PLA filaments with different spectroscopic behavior, in time-domain near infrared spectroscopy (TD-NIRS) and diffuse correlation spectroscopy (DCS) measurements on phantoms.

2. Materials and Methods

The geometry of the 3D printed objects was designed with Inventor Pro 2019 (Autodesk Inc., US) software. PLA and ABS objects were printed with a commercial 3D filament printer (Sharebot NG, Nibionno (LC), Italy; Filament diameter 1.75 mm).

2.1. *Optical characterization*

We optically characterized several 3D printed PLA and ABS thin sheets (0.3 mm thick, 20 mm per side). They were 3D printed as two layers with 100% infill, using filaments of different colors and companies. The PLA filaments were extruded at 205°C, whereas for the ABS filaments the extruder temperature was set to 250°C, and the plate was heated up to 80°C. To increase the first layer adherence of the filament, a 3D printing surface (Lokbuild, Coalville, UK) was laid on the printing bed. We measured their extinction coefficient spectra in the range from 300 nm to 1300 nm using a UV/VIS/NIR spectrometer (V570, Jasco Inc., Easton, USA), with a bandwidth of 1 nm (NIRS = 4 nm). Furthermore, we studied the effects of extruder temperature by printing the same filament (white filament from MDKOEM) at six different temperatures: 190°C, 195°C, 200°C, 205 °C, 210°C and 215°C. To prevent 3D printed objects from contamination, they were always handled with gloves.

2.2. *Phantom tests*

We tested the effects that different filaments had in DO acquisitions. In particular, we selected two black PLA filaments of different producers: FILOALFA and 3DiTALY, because of their different spectra. We 3D printed custom-designed probes for TD-NIRS and DCS applications. The geometry of the probe was similar to the one described in Re *et al.* [1]: light was 90° bended by optical prism (with 5x5 mm silver coated reflecting surface). The probes were 3D printed with 2 top and bottom layers and 20% rectilinear infill. For TD-NIRS measurements, we employed a device previously developed at the Department of Physics, Politecnico di Milano [2]. Laser light was emitted at two wavelengths: 689 nm (3mW maximum power) and 828 nm (8.5

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mW maximum power), and the backscattered light is collected at 3 cm distance.

For the DCS measurements, we used a device developed by the same authors [3]: highly coherent laser light (784 nm) with maximum nominal power of 120 mW was employed as injection source, and a single mode fiber led the reemitted light to the detection channel. The interfiber distance used for the DCS measurements was 1.5 cm, and optical prisms were used for bending both the injected and detected photons.

The two probes were used to perform measurements on phantoms: for TD-NIRS tests we used a solid calibrated homogeneous phantom, with $\mu_a = 0.14$ cm^{-1} and $\mu'_s = 20$ cm^{-1} @660 nm; for DCS, a liquid phantom made up of black Indian Ink, lipofundin and water was prepared ($\mu_a = 0.11$ cm^{-1}, $\mu'_s = 10.6$ cm^{-1} and diffusion coefficient $D_b = 1.2\ 10^{-8}$ cm^2/s, @ 785 nm).

3. Results

3.1. Optical characterization

In Fig. 1 a), spectra of the extinction coefficient (μ) of sheets printed with PLA filaments of the same company (MDKOEM), and different colors are presented. The spectra show different trends that varies with the color of the measured filaments (with extinction coefficient in the range 40<μ<75 cm^{-1}). Similar results were obtained for ABS filaments (not shown). In Fig. 1 b), we reported the spectra for the PLA sheets 3D printed with the same white filament (MDKOEM), at different extrusion temperatures: from 190°C to 215°C.

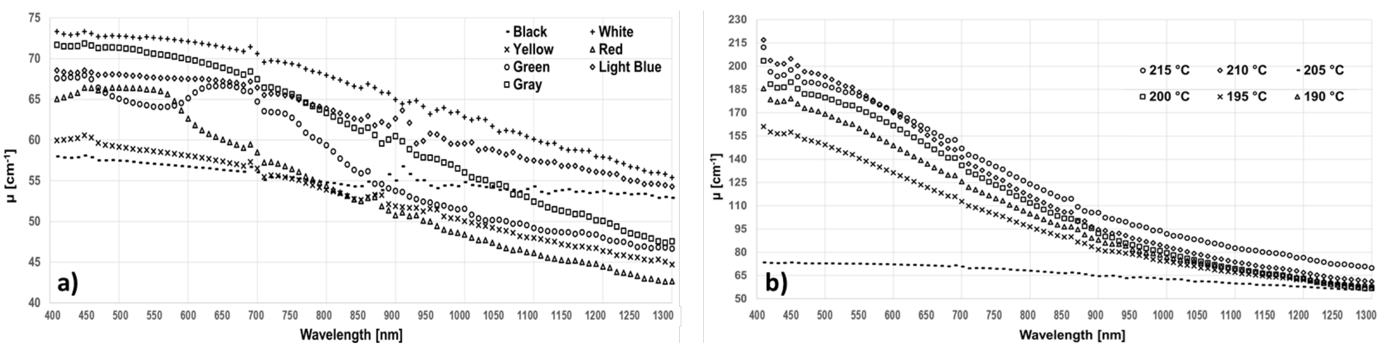

Fig. 1: Extinction coefficient spectra in the wavelength range 400-1300 nm for PLA filament: a) with different colors from the same producer (MDKOEM); b) with the same white filament (MDKOEM) 3D printed at different extrusion temperature.

In Fig. 2 we show the extinction coefficient spectra of the two black PLA filaments used for printing the probes for DO acquisitions. The spectra present different behaviors: for wavelengths higher than 700 nm the extinction coefficient for FILOALFA filament dramatically decreases, suggesting that this material is transparent for light at those wavelengths.

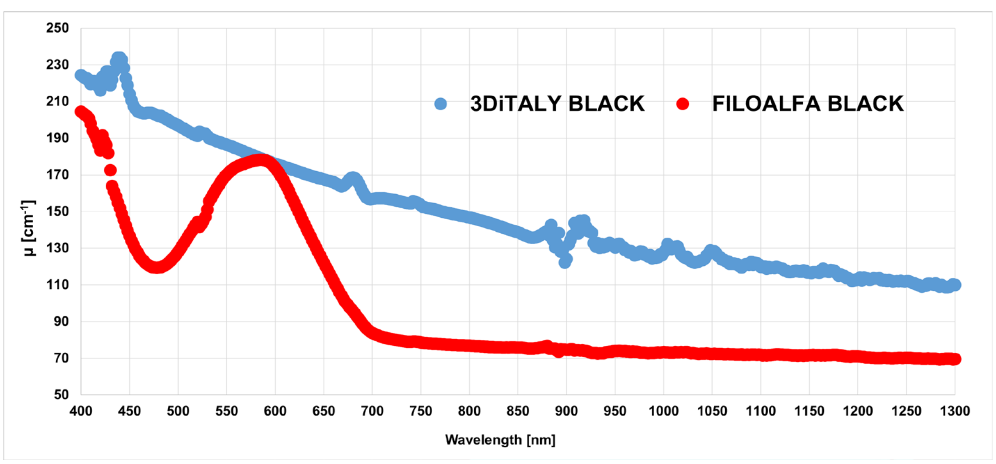

Fig. 2: Extinction coefficient μ spectra in the wavelength range 400-1300 nm for black PLA filaments employed to 3D print DO probes: FILOALFA and 3DiTALY producers.

3.2. Phantom tests

In Fig. 3 the signals acquired with the two probes (FILOALFA and 3DiTALY) on phantoms are shown: in panel a) we reported the photon Distribution of Time-of-Flight (DTOF) measured with TD-NIRS system @ 828 nm; in panel b) the intensity autocorrelation function (g_2) retrieved with DCS device. In panel a) a peak on the rising edge of the DTOF is clearly visible when the probe printed with FILOALFA filament is used. This suggests that some photons travelled inside the probe and reach the detection fiber without passing through the phantom. The DTOF measured @689 nm with FILOALFA probe does not present the peak on the rising edge of the curve. By fitting the acquired curves with the semi-infinite homogeneous model of the diffusion approximation, the results are not acceptable in case of the FILOALFA probe. The curve does not follow the expected diffusive behavior due to the direct light perturbation and the correct optical coefficients cannot be retrieved. In panel b) the intensity autocorrelation function decays later in time when the FILOALFA probe is used. This reflects more coherence in case of light detected with FILOALFA probe than with 3DiTALY probe. Indeed, the retrieved D_b of the liquid phantom estimated using the two probes are: $D_b^{FILOALFA} = (0.63\pm0.03)\ 10^{-8}\ cm^2/s$ and $D_b^{3DiTALY} = (1.16\pm0.06)\ 10^{-8}\ cm^2/s$, denoting that results obtained with 3DiTALY probe are closer to the nominal D_b.

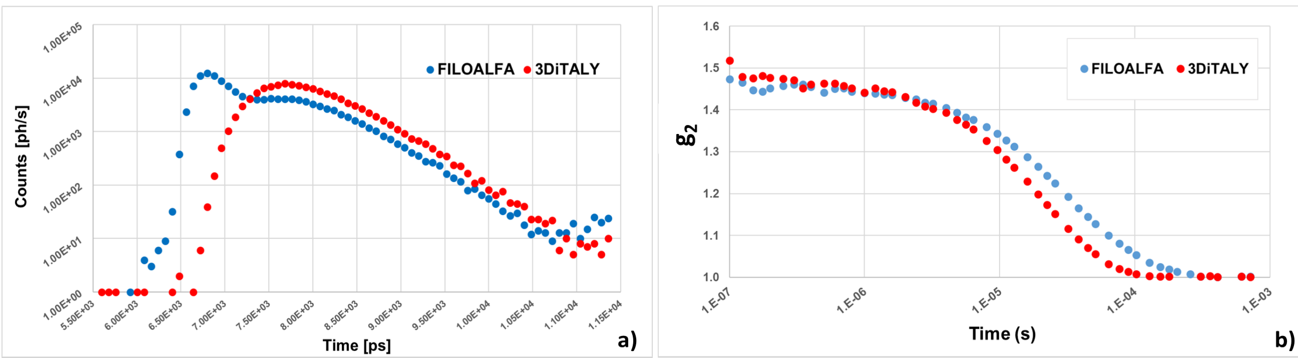

Fig. 3: In panel a): DTOFs acquired on the solid phantom @828 nm with TD-NIRS device. Y-axis is shown on a logarithmic scale. In panel b): Intensity autocorrelation functions acquired with a DCS instrument. In red (blue) the signal acquired with the probe printed with the PLA filaments from 3DItaly (FILOALFA).

4. Discussion and Conclusions

In this work we studied the optical properties of samples 3D printed with PLA and ABS filaments, and their effects on DO measurements. The results shown, highlight the influence of filaments color and printing specifications on optical properties of 3D printed objects. Even if the filaments are produced by the same company, differences in their spectra are observed, probably due to the presence of coloring agents as suggested by Wittbrodt *et al.* [4]. They demonstrated that some of the coloring agents could affect the crystallization rate, and influence the transmittance rate of the material itself. Moreover, we observed a variation in the extinction coefficient spectra with the extrusion temperature, in accordance with Ref. [4]. Finally, we tested two black PLA filaments when 3D printed for creating optical probes for DO. In Fig. 3, we have shown the negative effects that could be present in retrieved DTOFs when even black filaments are more transparent than expected. These results suggest that an optical characterization of 3D printed objects is needed before their employment in DO applications.

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