DEVELOPMENT OF FILAMENTS FOR THE ADDITIVE MANUFACTURING OF 3D-PRINTED FINELY SEGMENTED PLASTIC SCINTILLATORS

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Plastic scintillator detectors are very common in high-energy physics (HEP) experiments. Future HEP experiments will aim to build scintillator detectors comprising several million optically isolated scintillating voxels. The great advantage these detectors provide is particle tracking combined with calorimetric measurement of their energy loss, with sub-nanosecond response. 3D printing is a new technology for creating scintillators. It can also be used to produce other detector components, such as absorbers or reflective layers. This work presents features of the development of various filaments for 3D printing that can be used to create parts of scintillation detectors for high-energy physics.

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INTRODUCTION

Plastic scintillators are traditionally manufactured using cast polymerization [1], injection molding [2] or extrusion [3, 4] techniques. Afterward, they are shaped to fit the detector geometry through processes like machining or drilling. 3D printing enables new automated processes that simplify the production of finely segmented scintillators by allowing simultaneous printing of scintillation and reflective materials using two extruders [5].

Previously, we developed reflective filaments based on various polymer binders with the addition of titanium dioxide (TiO_2) for 3D printing of reflectors using Fused Deposition Modeling (FDM) technology, which can be used to create scintillation elements, in particular as part of finely segmented detectors The highest reflectivity was observed in filaments made from polystyrene (PS) and polymethyl methacrylate (PMMA) [5]. However, the PS-based filament was unsuitable for printing alongside the scintillation material, which was also made of polystyrene, as the materials were mixed during printing [6]. PMMA-based filament made it possible to print scintillation matrices of optically isolated polystyrene scintillators using FDM technology. The light yield was found to be quite uniform among the different cubes of the matrix, and the optical crosstalk was found to be less than 2% for the 3D-printed matrix layer, acceptable for applications that require a combined particle tracking and calorimetry [5].

Our further research into improving the geometric tolerances and transparency of the 3D-printed scintillator led to the development of a new 3D printing technology, which combines FDM and injection molding technology and is named Fused Injection Modeling (FIM) [7]. In this case, the reflector is printed as a matrix of empty cells using FDM technology. The cells are then filled by injecting melted scintillation filament using a specially designed nozzle. The polymer materials of the reflector must be able to withstand the injection of the scintillation filament melt at about 230 °C.

This work aims to develop, research, compare, and analyze reflective filament for 3D printing using different bases and reflector additives.

1. EXPERIMENTAL

As in our previous work [6], the reflective filaments were obtained using a Noztek ProHT desktop extruder [8]. We also used an industrial extruder Battenfeld and a winder Noztek Filament Winder 1.0 [9]. Granules of polymer were mixed with the additive powders, which were added and mixed for 20 min. The resulting mixture was loaded into the extruder, and filaments with a diameter of (1.75±0.1) mm were extruded at 260…270 °C.

The Creatbot F430 [10] 3D printer with two extruders was used for printing samples of reflective materials for optical investigation. Using the obtained filaments, 0.2, 0.4, and 1 mm thick reflector samples were printed at 265 °C. The area of all samples was 20x20 mm.

A Shimadzu-2450 spectrophotometer with the integrating sphere was used to perform measurements of light transmittance T and optical reflection R in the range from 200 to 800 nm [6]. Measurement error – 0.5%.

2. RESULTS OF STUDIES AND THEIR ANALYSIS

First, we needed to choose a reflector additive. For this, pressed reflector powders were prepared. It was pressed powders of PTFE (polytetrafluoroethylene), TiO_2 and TiO_2:PTFE (2:1 ratio).

The selected reflectors in the region of scintillation polystyrene luminescence, with a peak at approximately 420 nm, have reflectivities of 101.81% (for PTFE), 94.64% (for TiO_2), and 94.3% (for TiO_2 + PTFE). At the same time, pure PTFE has a high reflectivity value (more than 100%) from 260 nm, in contrast to pure TiO_2, which shows more than 60% reflection in the region >400 nm, and more than 80% in the region >410 nm. Mixing TiO_2 and PTFE powders in a 2:1 ratio does not increase reflection in pressed powders.

After that, filaments of different polymers with reflective additives were created and samples with 0.2, 0.4, 1.0 mm thickness h were 3D-printed.

The best reflective additive in polycarbonate (PC) is a mixture of TiO_2 (10%) and PTFE (5%).

A 3D-printed sample with a thickness of 0.2 mm is comparable to a PC + TiO_2 (15%) sample with thicknesses of 0.4 and 1 mm in the 410…450 nm range. Samples PC with TiO_2 (20%) demonstrate the lowest reflection among the presented samples, which is associated with increased brittleness and porosity as the TiO_2 concentration in PC increases.

The optimal thickness of a printed sample for use in the 420 nm reflection range is 0.4 mm, regardless of the additive concentrations presented. Samples with a thickness of 0.2 mm are also effective, though their reflectance is approximately 2…3% lower.

PC samples with TiO_2 (10%) and PTFE (5%) exhibit lower light transmittance compared to PC + TiO_2 (15%) samples.

The lowest light transmittance is found in samples with a thickness of 1 mm. However, for samples with a thickness of 0.4 mm, light transmittance at 420 nm remains within the range of 0.3…0.6%, which is already a good result for reflective materials.

Therefore, the optimal reflective additive for incorporating into polycarbonate and subsequent 3D printing is a mixture of TiO_2 (10%) and PTFE (5%). Among other additive concentrations shown in this paper, these samples achieve the highest reflection coefficient (86.22%) in the 420 nm range. The minimum working thickness is 0.2 mm (R=83.35%), while the optimal thickness is 0.4 mm (R=86.22%). This thickness is associated with light transmittance for h=0.2 mm (T=3.6%) and h=0.4 mm (T=0.55%).

To compare T and R values, a reflective additive (10% TiO_2 and 5% PTFE) was introduced into the PMMA base, and samples of varying thicknesses were 3D-printed.

PMMA-based samples exhibit higher light transmittance T than PC-based samples. At the same time, PMMA-based samples show better light reflection R than PC-based samples. The reflection and transmittance values at a wavelength of 420 nm for 3D-printed PMMA and PC samples for comparison are shown in Table 1.

Since PMMA-based samples demonstrate higher light reflection (R=90.53% at h=0.4 mm) at 420 nm compared to PC-based samples (R=86.22% at the same thickness), they may be considered as potential base materials for reflectors. However, it should also be noted that their light transmittance is significantly higher than that of PC, for example, for a sample thickness of 0.2 mm, T_{PMMA}=10.36% versus T_{PC}=3.6%, and for a thickness of 0.4 mm, T_{PMMA}=3.69% versus T_{PC}=0.55%.

What about 3D-printing samples of PMMA with only TiO_2 without PTFE? To answer this question, a filament based on PMMA with additive TiO_2 (15%) was created, and samples were 3D-printed.

PC-based samples exhibit higher light transmittance than PMMA-based samples, and PMMA-based samples show better light reflection than PC-based samples. The reflection and transmittance values at a wavelength of 420 nm for 3D-printed PMMA and PC samples for comparison are shown in Table 2.

Since PMMA-based samples demonstrate higher light reflection (R=91.95% at h=0.2 mm) at 420 nm compared to PC-based samples (R=85.07% at the same thickness), they may be considered as potential base materials for reflectors. However, it should also be noted that the softening temperature of PMMA is lower than that of PC.

Table 1

Comparison of the values of light reflection R and light transmittance T for 3D-printed samples of PMMA and PC with different thickness at λ = 420 nm. Reflective additive – TiO_2 (10%) and PTFE (5%)

λ = 420 nm	R, %			T, %		
Thickness of 3D-printed samples	0.2 mm	0.4 mm	1.0 mm	0.2 mm	0.4 mm	1.0 mm
PMMA + TiO_2 (10%) and PTFE (5%)	84.73	90.53	92.07	10.36	3.69	0.1
PC + TiO_2 (10%) and PTFE (5%)	83.35	86.22	89.27	3.6	0.55	0.01

Table 2

Comparison of the values of light reflection R and light transmittance T for 3D-printed samples of PMMA and PC with reflective additive – TiO_2 (15%)

λ = 420 nm	R, %	T, %
Thickness of 3D-printed samples	0.2 mm	0.2 mm
PMMA + TiO_2 (15%)	91.95	1.57
PC + TiO_2 (15%)	85.07	3.81

CONCLUSIONS

To achieve a higher light reflection R value in the case of introduction into PC samples, combining TiO_2 and PTFE additives is necessary. In this case, the efficiency of light reflection increases. When introducing reflective additives into PMMA samples, there is no need to combine additives; only TiO_2 as a reflector is sufficient. This is because the combined compositions were created for environments with lower light transmittance. The additional reflector component does not increase the light reflection value in more transparent environments. However, this may also be due to the conditions and parameters of 3D printing.

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РОЗРОБКА ФІЛАМЕНТІВ ДЛЯ АДИТИВНОГО ВИРОБНИЦТВА ДРОБНОСЕГМЕНТОВАНИХ ПЛАСТИКОВИХ СЦИНТИЛЯТОРІВ, НАДРУКОВАНИХ ЗА МЕТОДУ 3D

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Пластикові сцинтиляційні детектори дуже поширені в експериментах із фізики високих енергій (ФВЕ). Майбутні експерименти з ФВЕ будуть спрямовані на створення сцинтиляційних детекторів, що містять кілька мільйонів оптично ізольованих сцинтиляційних вокселів. Великою перевагою, яку забезпечують ці детектори, є відстеження частинок у поєднанні з калориметричним вимірюванням їх втрат енергії з субнаносекундним відгуком. 3D-друк – це нова технологія створення сцинтиляторів. Її також можна використовувати для виробництва інших компонентів детекторів, таких як поглиначі або відбивні шари. Представлено особливості розробки різних ниток для 3D-друку, які можна використовувати для створення деталей сцинтиляційних детекторів для фізики високих енергій.