

Investigation of the properties changes observed for plastic samples made by fused deposition modelling under radiation exposure

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Abstract. This work shows investigation of the transmission dynamics of polymer samples made of PLA plastic (polylactide) by fused deposition modelling for electron beam. Besides, results of tests for mechanical destruction (compression) of plastic samples with radiation exposure and without are shown. Article demonstrates that properties of plastic samples are stable up to 1.5 kGy, that proves the suitability of this material for sample production intended for depth dose distributions of electron beams.

1. Introduction

High energy electron beams are used for radiation therapy purposes since 1947 when irradiation by extracted betatron beam was first successfully carried out [1, 2]. Modern medical linear accelerators (linacs) generate electron beams with 4–25 MeV average energy [2, 3]. Advantages of electron using for radiotherapy purposes are possibility to provide higher dose homogeneity in the target volume as well as sufficiently lower dose value in deeper located healthy tissues. The latter leads to achieve the main goal of radiotherapy – maximal damage of malignant tumor while minimizing the impact on normal tissue [1–3].

The common method for radiation field depth dose distribution of radiation beam forming involve using of wedge filter sets, included in the accelerator package. The limited wedge number and shapes cannot provide forming of arbitrary complex dose distributions [1, 2]. These filters are designed for gamma radiation beam and cannot be used for electron one. These limitations significantly affect accuracy of dose delivery to the tumor focus and leads to overexposure of healthy tissue [2]. To form depth dose distributions of electron beam radiation fields and avoid acute post-radiation reactions some medical centers apply either special complex shaped compensators, which are located in the beam path and change its transverse profile, or tissue equivalent boluses located on the patient's body, which provides changes of the depth dose distribution in the patient tissues [3, 4]. Shapes of compensators and



boluses is chosen individually for each particular patient, that causes increase the time of preparation for treatment, necessary to produce samples with complex shape [2–4].

In order to increase accuracy and for simplification of patient specific forming samples production, authors of this work propose to use fast prototyping systems. The technical level of these systems allow producing produce custom-made products with submillimeter accuracy in very short time [5, 6]. A number of papers poof the efficiency of this approach [5, 7–10].

The PLA plastic is chosen as investigated material for forming samples production since it is relatively cheap, highly available and strength [11].

Nowadays a number of investigations of physical and mechanical properties of polymers under irradiation by electron beam aimed to improve material parameters are carried out [12–14]. Based on results of a few works [12–14] it can be concluded that physical and mechanical properties of different polymers are stable in radiation dose range equal up to 100 kGy. The total dose in a radiation therapy course is not higher than 100 Gy [15], that 1000 time lower than aforementioned dose range. However, for forming of depth distributions of radiation fields it is necessary to investigate not only mechanical properties, but also ionizing radiation transmission dynamics of this material.

Therefore, the aim of the work is to investigate transmission dynamics of PLA plastic for electron beam and to test this material for mechanical destruction (compression) of plastic samples exposed and non-exposed to radiation.

2. Materials and methods

2.1. Production of plastic samples

In a frame of work samples made of PLA plastic is produced using fused deposition modelling by 3D printer Ultimaker2 with modified printhead [16]. The samples are cubic shaped with 2 cm edge length and 100% filling coefficient in accordance with ISO 604:2002 (federal standard 4651–2014) [17]. The number of samples for each type of test equals to 3 (Figure 1). The model of samples for 3D printing is made with Siemens NX software, while Slic3r software is used for layer separation [18, 19].



Figure 1. Samples made of PLA plastic using fused deposition modeling technology.

2.2. Experimental scheme.

The TPU microtron is used as a source of radiation [20]. The PLA samples is placed in the path of the extracted electron beam with 6 MeV energy at 15 cm distance from the exit window (Figure 2).

Dose rate measurement is performed using clinical dosimeter UNIDOS E with plane-parallel ionization chamber Markus type 23343, placed in the special adapter plate of solid phantom RW3 [21–23]. Dose rate of initial beam in absence of sample equals 8.93 Gy/minute (S_0). Current value is measured each minute (S_i). Total dose absorbed by the each irradiated sample equals 1.5 kGy.



Figure 2. Experimental scheme: 1 – ionizing radiation source; 2 – plastic sample; 3 – ionization chamber; 4 – tissue equivalent phantom.

2.3. Mechanical tests

Investigation of mechanical properties of plastic samples with radiation exposure and without is performed with Instron 5982 setup [24]. Compression tests are performed with 100 kN load sensor and the speed of movement of the loading plate equal to 1mm/minute at room temperature. Load dependence on motion is measured using Bluehill software [25]. Figure 3 shows appearance of the experimental setup.



Figure 3. Mechanical test of plastic samples with Instron 5982 setup.

2.4. Results processing

In accordance with ISO 604:2002 (federal standard 4651–2014) following parameters is determined for both irradiated and non-irradiated samples: compressive yield stress, ultimate compression strength, elastic modulus.

Compressive yield strength was determined as the compression stress value for the sample height reduction on less than twice. On the other hand, PLA plastic is a glass-crystalline polymer, so at yield stress it can be considered as destructed since crystalline part is still stable. Therefore, total fracture was defined as the ultimate compressive strength with a decrease in height of more than twice.

Compressive stress (MPa) is determined by the equation:

$$\sigma = \frac{F}{A} \quad (1)$$

where F – compressive load, (N); A – sample initial cross-sectional area, mm^2 .

Elastic modulus (MPa) is determined by the equation:

$$E_c = \frac{\sigma_1 - \sigma_2}{\varepsilon_1 - \varepsilon_2} \quad (2)$$

where σ_1, σ_2 – compressive stress, measured at relative deformation values $\varepsilon_1, \varepsilon_2$, (MPa);

Relative compressive deformation value is determined by the equation:

$$\varepsilon = \frac{\Delta L_0}{L_0} \quad (3)$$

where ΔL_0 – reduction of the nominal sample length, mm; L_0 – nominal sample length, mm [17].

3. Results and discussions

The measurement results of transmission dependence of investigated polymer samples for electron beam on absorbed dose are shown in Figure 4. The results of each measurement with investigated sample (S_i) is normalized on value of initial dose rate in absence of sample (S_0), so it shows relative part of radiation passed through the sample $k=S_i/S_0$.

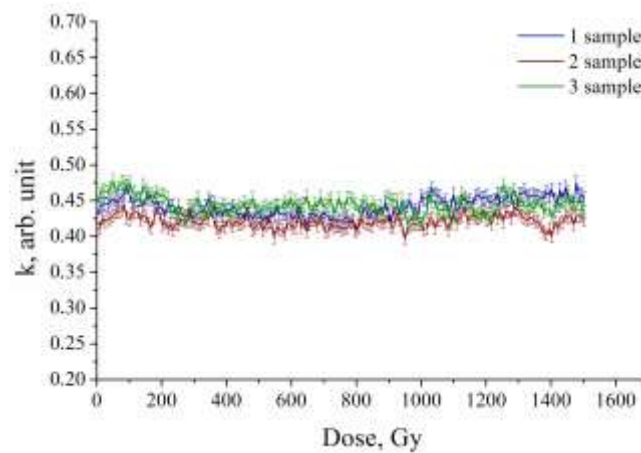


Figure 4. Dependence of 3D printed polymer samples transmission for electron beams on absorbed dose. The samples made of PLA plastic using fused deposition modeling.

Figure 4 shows slight deviation of transmission dynamics for electron beam. This deviation is about $\sim 2\%$ and stable in time, that proves the possibility of investigated material and samples made of it to maintain absorption properties for high energy electrons even with high doses of absorbed radiation (up to 1.5 kGy).

Figure 5 shows appearance of samples made of PLA plastic after compression tests.



Figure 5. Samples made of PLA plastic 3D printed using fused deposition modeling after compression tests.

As one can see in Figure 5, the samples under compression is deformed without gaps or cracks.

The results observed in compression tests of plastic samples are shown graphically: σ_Y – compressive stress at material yield strength (Figure 6), σ_M – ultimate stress in compression with the ultimate destruction of the material (Figure 7).

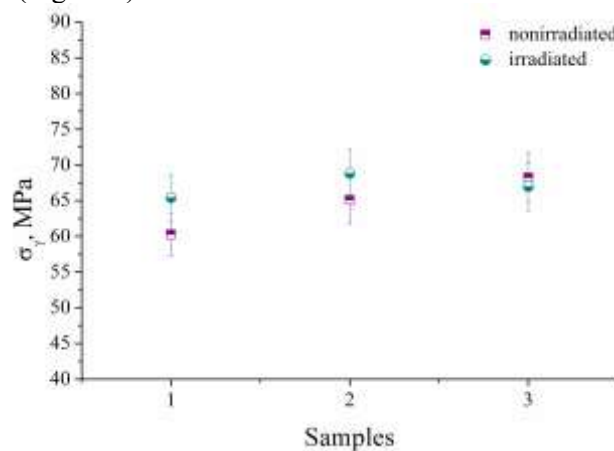


Figure 6. Experimentally observed compressive yield stress for irradiated and non-irradiated samples made of PLA plastic using fused deposition modeling.

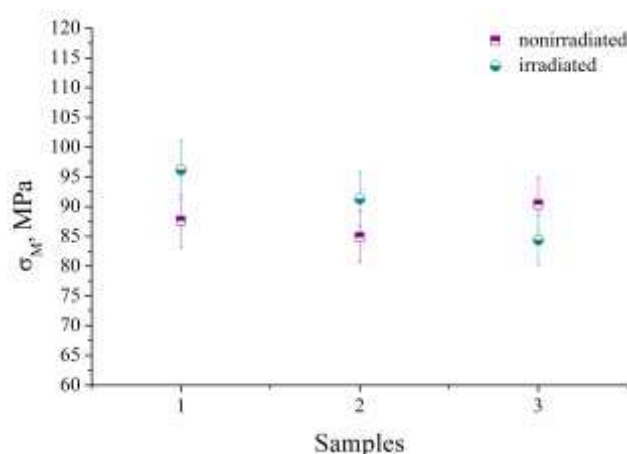


Figure 7. Experimentally observed ultimate compression strength for irradiated and non-irradiated samples made of PLA plastic using fused deposition modeling.

Figure 8 shows results of elastic modulus determining (E_C) for plastic samples.

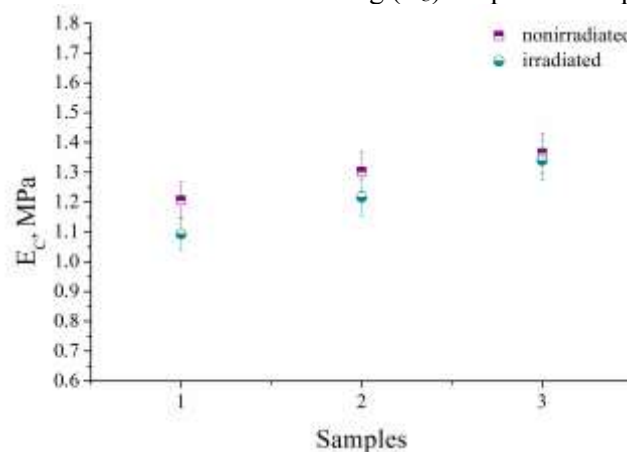


Figure 8. Experimentally observed elastic modulus for irradiated and non-irradiated samples made of PLA plastic using fused deposition modeling.

As one can see from Figures 6–7, the data obtained for irradiated and non-irradiated samples agree within the error. Figure 8 shows that all three irradiated samples have lower strength. As far as elastic modulus is more demonstrative integral characteristic of strength, this effect can be caused by slight structural change in plastic with increasing crystallinity. However, elastic modulus reduction does not exceed 7%. Accounting low statistical sample, this data can relate to the error of the experiment. Summarizing the above, it can be concluded that samples made of PLA plastic using fused deposition modeling maintain mechanical properties in dose range up to 1.5 kGy.

4. Conclusion

The work demonstrates, that samples made of PLA plastic using fused deposition modeling maintain both mechanical and absorption properties, after absorbing of radiation dose up to 1.5 kGy, that proves prospects of this material using for production of samples forming depth dose distribution of electron beams.

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