The use of thermoplastic polyurethane composites to develop a model of the renal pelvicalyceal system by 3D printing

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Abstract: Composites based on thermoplastic polyurethanes (TPUR) were obtained using the twin-screw extrusion method. Influence of the addition of 6–8 wt% silica and 1–3 wt% aluminum oxide and 1–3 wt% dibutyl phthalate (plasticizer) on Rockwell hardness, Charpy impact strength and tensile mechanical properties was assessed. The best properties were obtained for a composite containing 8 wt% silica, 3 wt% aluminum oxide and 3 wt% dibutyl phthalates. For this composite, the renal pelvicalyceal system was obtained using the FFF method.

Keywords: thermoplastic polyurethane, silica, aluminum oxide, anatomical structures, FFF.

Zastosowanie termoplastycznych kompozytów poliuretanowych do opracowania modelu układu kielichowo-miedniczkowego nerki metodą druku 3D

Streszczenie: Metodą dwuślimakowego wytłaczania otrzymano kompozyty na bazie termoplastycznych poliuretanów (TPUR). Zbadano wpływ dodatku 6–8% mas. krzemionki i 1–3% mas. tlenku glinu oraz 1–3% mas. ftalanu dibutylu (plastyfikator) na twardość Rockwella, udarność Charpy'ego i właściwości mechaniczne przy rozciąganiu TPUR. Najlepsze właściwości uzyskano dla kompozytu zawierającego 8% mas. krzemionki, 3% mas. tlenku glinu oraz 3% mas. ftalanu dibutylu. Dla tego kompozytu metodą FFF otrzymano układ kielichowo-miedniczkowy nerek.

Słowa kluczowe: poliuretan termoplastyczny, krzemionka, tlenek glinu, struktury anatomiczne, FFF.

Three-dimensional (3D) printing technology is often presented as one of the leading modern technological advances and is extensively applied in medical science, where 3D digital models of the human body are being constructed using computed tomography (CT) or magnetic resonance imaging (MRI). Several materials can be applied, including acrylonitrile-butadiene-styrene, polylactic acid, polyvinyl alcohol, polyamides, polyethylene and wood, metal and carbon fibres [1]. For many surgical areas, 3D printing methods support the operating surgeon both at the diagnostic and treatment planning stages, but also at the therapeutic stage, when printed models of the organs together with the pathological structures requiring treatment allow the surgery to be performed more precisely. Polymer composites are becoming part of everyday practice in the areas of orthopedics [2], maxillofacial surgery [3], plastic surgery [4] or urology [5, 6], and the published results of studies on the feasibility of 3D technology in surgery unambiguously show its high merit, especially in improving treatment outcomes. The 3D modelling and printing are likewise an indispensable teaching tool in medicine. To begin with anatomical didactics, 3D models are increasingly supplementing traditional anatomy specimens in anatomy departments [7]. The increasing quality of polymer composites makes it possible to produce overly complex anatomical structures and the technologies used enable multicolor printing of individual organs with almost identical topography, relations and the anatomical course of vessels and nerves supplying them. The 3D printing methods are also an essential part of the development of medical simulation, which is currently an everyday practice for all medical students [8, 9]. The wide range of possibilities for the use

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of polymer composites to produce medical simulators allows all parts of the selected medical procedure to be learned under supervised circumstances by an experienced operator [10]. Medical simulation is a safe procedure since we eliminate the steps of setbacks resulting from a learning curve on a real patient. Endourological procedures for the treatment of urinary stones are currently the most performed surgeries in urology [11]. The surgical approach to the treatment of nephrolithiasis is progressing towards reducing the invasiveness of the procedure with the highest possible stone free rate (SFR), that is, the highest percentage of patient free from stones. For nephrolithiasis with stones less than 20 mm localized in the pelvicalyceal system, the treatment of choice is retrograde intrarenal surgery (RIRS) [12]. RIRS is a minimally invasive procedure, commonly used in urology, which allows the use of modern technology such as a laser and a fibroscope (a flexible ureterorenoscope with a working channel) [13].

The objective of the research was to develop composites based on TPUR incorporating selected fillers (colloidal silica, aluminum oxide) with enhanced functional properties and good dimensional stability. These composites are intended for use in creating structures of the renal pelvicalyceal system based on CT images of a real patient using 3D printing with the method of depositing melted polymer. The model enables a urology resident improving their skills to obtain experience in the treatment of nephrolithiasis by retrograde intrarenal surgery. The model produced allows a trainer of the RIRS procedure to be developed and repeatable simulations of the surgery to be conducted, considering anatomical aspects corresponding to real conditions in the patient's body. The polymer model obtained by 3D printing enables the operator to practice the manual skills necessary to conduct such a procedure, as well as to optimize the laser settings (laser pulses and their power) during the procedure.

EXPERIMENTAL PART

Materials

Thermoplastic polyurethane, TPUR, (diisocyanate of hexamethylene with ethylene glycol in a 1:2 ratio), Aerosil COK84 colloidal silica, SiO_2, (Evonic Industries, Hanau, Germany), aluminum oxide, Al_2O_3, (Warchem, Zakręt, Poland), dibutyl phthalate (Warchem, Zakręt, Poland) was used in the research.

Preparation of composites

The mixing process was carried out using a ZSK 18DL twin-screw extruder (Coperion, Stuttgart, Germany) equipped with a granulation line. The following process parameters were used: screw speed 350 rpm, output 3 kg/h, temperature 200–220°C. Filaments with a diameter of approximately 1.75±0.05 cm were then produced from the obtained composites, using a fiber production line from Gamart (Jasło, Poland) with the following parameters: temperature 195–200°C, extrusion speed 100 rpm, removal speed 100 mm/s, winding speed 80 mm/s. The composition of the composites is listed in Table 1.

Preparation of samples

Samples for mechanical testing were obtained in accordance with the PN-EN ISO 527-2 standard by the Fused Filament Fabrication (FDM) method using a Prusa i3 MK3 3D printer (Prague, Czech Republic). The following

T a b l e 1. The composition of the composites

Sample	TPUR, wt%	SiO_2, wt%	Al_2O_3, wt%	Dibutyl phthalate, wt%
K0	100	–	–	–
K1	92	6	1	1
K2	91	7	1	1
K3	90	8	1	1
K4	90	6	2	2
K5	89	7	2	2
K6	88	8	2	2
K7	88	6	3	3
K8	87	7	3	3
K9	86	8	3	3
K10	91	8	–	1
K11	90	8	–	2
K12	89	8	–	3
K13	96	–	3	1
K14	95	–	3	2
K15	94	–	3	3

printing parameters were used: nozzle diameter 0.4 mm, layer height 0.2 mm, filling degree 100%, straight linear filling pattern ±45⁰, extrusion temperature 220°C, print bed temperature 60°C, printing speed 60 mm/s.

Obtaining physical models using the FFF technique

The physical models were created additively using the Fused Filament Fabrication (FFF) technique, which is classified according to the ISO/ASTM DIS 52900 standards as one of the basic additive manufacturing processes, in particular material extrusion. The parameters of the FFF modeling process were determined based on the imported STL model using dedicated RP software for the PrusaSlicer production machine (Prusa, Prague, Czech Republic). The slicer not only allows you to divide layers according to the height set in the software, but also considers many other important parameters of the additive process. The main parameters include the previously mentioned height of the applied layer, extrusion temperature, table temperature, density and type of filling, and the speed of applying the thermoplastic material. It is also worth mentioning the need to create supporting structures, which in the Original Prusa I3 MK3 device (Prusa, Prague, Czech Republic) are made of the same material and require mechanical removal after the process.

Methods

The Rockwell hardness was measured according to ISO 6508 standard using a Zwick/Roell hardness tester (Zwick GmbH & Co., Ulm, Germany) at room temperature. Ten determinations were conducted for each series. Notched Charpy impact strength was determined according to ISP/179/1Ea standard using a PSW Gehard Zorn impact hammer (Stendal, Germany) with a force of 1 J. Five measurements were conducted for each series. Static tensile properties were performed according to ISO 527 using an Instron 5967 testing machine (Instron, Grove City, PA, USA) at room temperature. The Young's modulus was measured at a given tensile speed of 5 mm/min (until 1% tensile strain was achieved), and then the speed was increased to 50 mm/min. Five measurements were performed for each series.

RESULTS AND DISCUSSION

Mechanical properties

The Rockwell hardness, Charpy impact strength, and tensile properties are listed in Table 2. It was found that the content of the fillers used significantly improved mechanical properties of TPUR-based composites. The highest Rockwell hardness (increase by approximately 18%) was obtained for K9 composite containing 8 wt% SiO_2 and 3 wt% Al_2O_3. Such a significant increase in this parameter is due to the proper dispersion of silica, which, as known from the literature, improves hardness [10]. In the case of Charpy notched strength, the best results were also obtained for the K9 composite, where the impact strength increased by as much as 34% compared to TPUR. Comparable results were obtained by Niaza and co-authors [11]. Moreover, the addition of fillers increased the Young's modulus (6–19%). This behavior is consistent with reports of other researchers [12]. The greatest improvements in tensile strength at break of 21 and 24% were observed for K6 and K9 composites, respectively. This can be explained by the synergistic

T a b l e 2. Mechanical properties of the composites

Sample	Rockwell hardness N/mm²	Charpy strength kJ/m²	Young's modulus MPa	Tensile strength at break, MPa	Elongation at break %
K0	29.9±1.1	4.6±0.4	1259±21	24.3±1.1	10.8±0.2
K1	31.1±1.7	5.1±0.2	1323±16	27.3±1.2	10.0±0.4
K2	32.3±0.9	5.7±0.4	1344±18	28.4±1.9	9.1±0.2
K3	33.1±1.4	6.2±0.3	1492±12	30.9±1.3	8.6±0.4
K4	32.1±1.6	5.9±0.3	1396±23	28.3±1.2	9.0±0.1
K5	33.4±1.7	6.5±0.3	1400±18	29.1±1.3	9.4±0.9
K6	34.3±1.7	6.8±0.7	1417±18	30.6±1.9	10.7±0.1
K7	33.8±1.4	6.6±3.5	1407±13	30.4±0.8	11.0±0.4
K8	34.2±1.1	7.0±0.3	1471±19	31.4±1.7	11.1±1.2
K9	35.2±0.9	7.0±0.2	1503±10	32.2±1.4	12.0±0.3
K10	30.9±0.6	5.2±0.7	1362±10	26.9±0.7	9.7±0.2
K11	31.3±0.4	5.7±0.6	1334±11	27.4±1.4	10.4±0.2
K12	32.6±0.4	5.9±0.4	1402±10	29.9±1.3	11.2±0.4
K13	28.9±0.8	4.9±0.3	1392±11	26.9±1.2	9.4±0.1
K14	29.8±1.1	5.2±0.2	1298±12	27.2±1.1	10.4±0.4
K15	30.2±0.8	5.5±0.2	1315±12	27.9±1.2	11.3±0.2

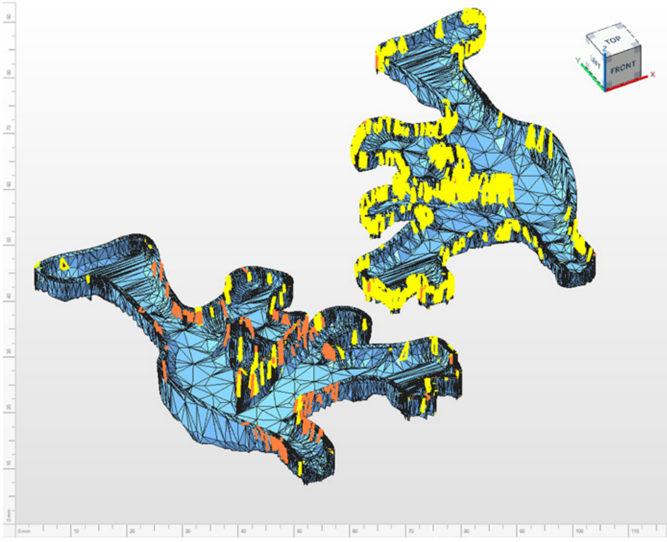

Fig. 1. Errors in the triangular mesh of the anatomical model

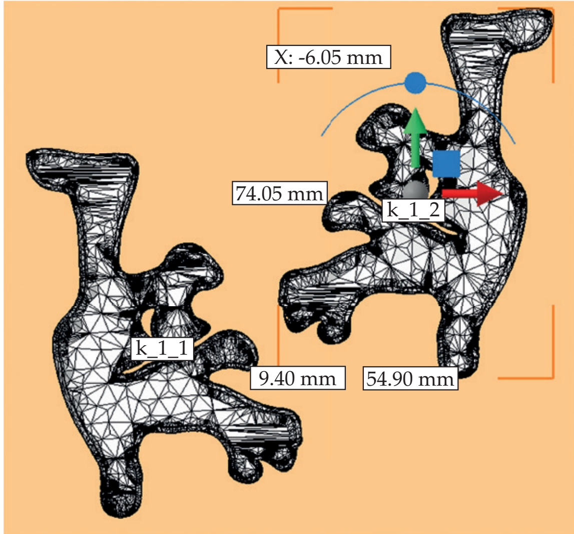

Fig. 2. Scaling the anatomical model while maintaining the size and amount of the triangular mesh

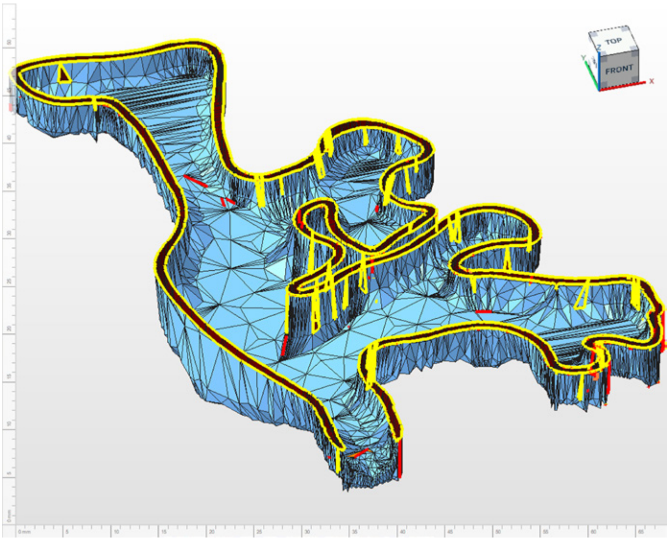

Fig. 3. Improving the triangular mesh of the anatomical model

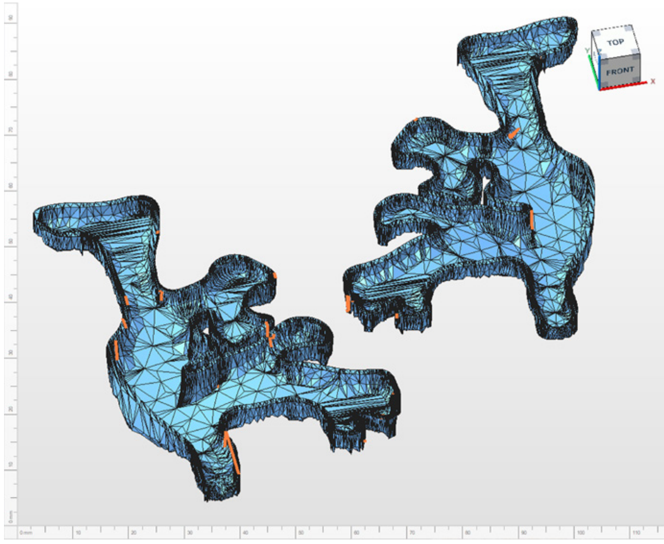

Fig. 4. The finished mesh model of the anatomical model

effect of both fillers. As expected, the addition of all fillers reduced the elongation at break from 10.8% (TPUR) to even 8.9% (K3). It should be emphasized that the use of the plasticizer significantly increased the elongation. This is a desirable phenomenon in the case of flexible anatomical models of the pelvicalyceal system.

Preparation of the pelvicalyceal system structures using 3D printing

Tessellation was performed based on 3D CAD models obtained by processing DICOM data. The surfaces of the anatomical model were approximated using a triangle mesh, and then an STL model was generated in binary format preserving the unit (mm) with high resolution parameters according to the Autodesk Inventor environment options: surface deviation 0.005%, normal deviation 10, maximum edge length 100%, aspect ratio 21.5. The STL file is saved in a format that allows cooperation with software dedicated to a specific additive manufacturing process (a specific production machine).

The next stage of the research was the analysis and verification of the data obtained in the tessellation process. Verification of the generated triangle mesh describing individual research models aims to eliminate or correct errors in the processing and tessellation of 3D CAD data.

The errors concern the lack of elementary triangles (incorrectly determined coordinates of vertices and normal vectors), intersecting and/or duplicating triangles, and mesh discontinuities in areas of complex geometric changes of the model (transitions between different surfaces). Mesh analysis and verification were performed in Autodesk Netfabb (Autodesk, San Rafael, CA, USA).

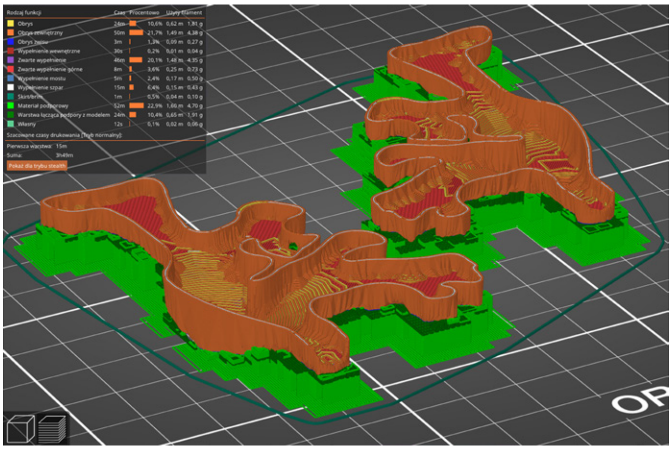

Fig. 5. Anatomical models in the PrusaSlicer software environment

The Autodesk Netfabb software environment with errors in the STL file is shown in Fig. 1. Additionally, this program conducted a scaling process while maintaining the appropriate size and number of triangles (Fig. 1). The process of repairing anatomical models was multi-stage. An example process for repairing anatomical models in Autodesk Netfabb software is shown in Fig. 2–4. Figure 5 shows anatomical models with support structures, with basic manufacturing profiles such as layer height and material used during the process in PrusaSlicer.

The model was obtained from the selected K9 composite based on mechanical tests. The resulting model of the pelvic-renal system, thanks to the development of the hybrid K9 composite, showed comparable properties and flexibility compared to the actual human kidney element.

Currently, rapid prototyping techniques are used in various fields, including in the aviation and automotive industries. In recent years, polymer materials and 3D printing have become increasingly popular in medicine, e.g., for visualizing the geometry of anatomical structures and producing surgical templates or implants [17, 18]. The development of new polymer materials based on thermoplastic polyurethane with the addition of a hybrid mixture of fillers (silica and aluminum oxide) for 3D printing allowed for more accurate structure shaping and improved dimensional stability of printed anatomical models [19, 20]. These alleviated adverse effects resulting from the physicochemical properties of polymers, such as warping and shrinkage. The properties of these polymer composites enable greater precision in the use of 3D printing technology and improve the quality of the resulting anatomical structures. Additionally, the use of a plasticizer, dibutyl phthalate, increased the flexibility of printed anatomical models, bringing their properties closer to human organs. Such anatomical elements can be used to create simulators of specific surgical procedures and allow for the improvement of surgical techniques and the improvement of the quality of procedures performed on patients in safe and controlled ex vivo conditions.

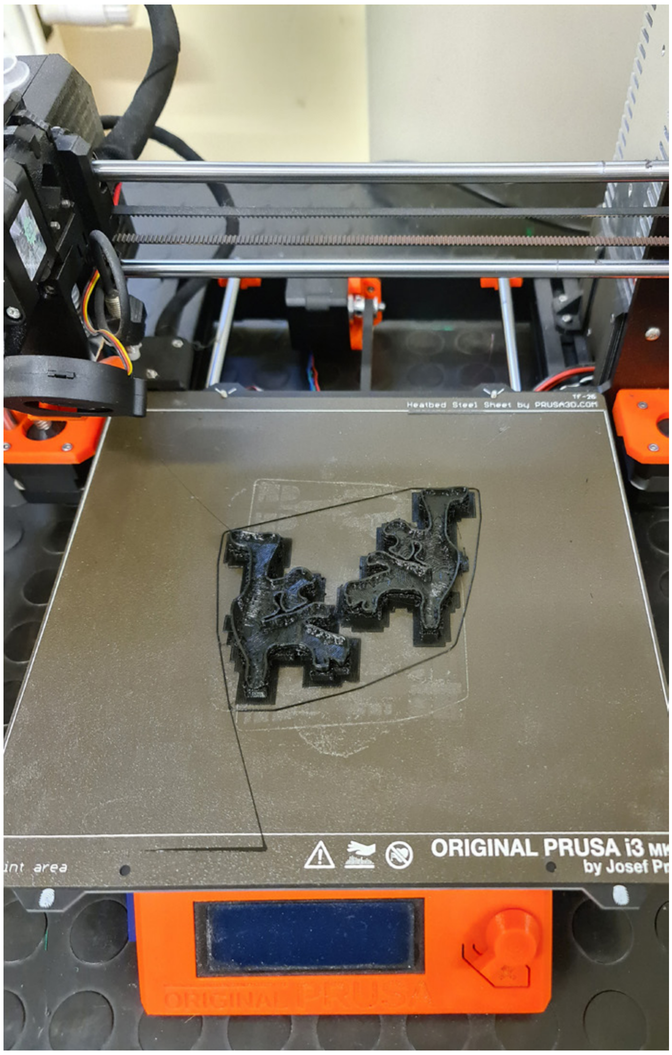

Fig. 6. Anatomical models obtained using 3D printing from K9 composite

Ethically, the use of 3D-printed models can significantly reduce the need for cadaveric specimens, which are often limited in availability and can raise ethical concerns. By using models that are ethically sourced, we can provide more training opportunities without ethical compromises.

CONCLUSIONS

Authors successfully obtained thermoplastic polyurethane (TPUR) composites with various content of selected fillers and assessed their selected mechanical properties. The best test results were obtained for a composite K9 containing 8 wt% SiO_2, 3 wt% Al_2O_3 and 3 wt% dibutyl phthalates. Using the FFF method, the pelvicalyceal system was obtained from this composite. The printed model provides a realistic, effective, and ethical alternative to traditional methods of training medical students. This research addresses current limitations of material properties, showing technological progress, in which 3D printed models will likely become valuable addition and integral to medical education and surgical practice.

Authors contribution

K.B. – conceptualization, formal analysis, investigation, resources, data curation, writing-original draft, supervision, editing. Ł.P. – conceptualization, formal analysis, investigation, resources, methodology, visualization, writing-original draft. All authors have read and agreed to the published version if the manuscript.

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Conflict of interest

The authors declare no conflict of interest.

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