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Experimental and numerical determination of mechanical properties of porous thermoplastic

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ABSTRACT

The main aim of this paper is to experimentally and numerically determine the mechanical properties of thermoplastics that exhibit porosity due to 3D-printing. The mechanical properties of thermoplastics (polyacrylonitrile-co-butadiene-co-styrene, polycarbonate, polyetherimide) were investigated using both tensile testing machine and finite element method. The object of the study is the standard 3D-printed specimen for tensile testing. According to the result of the experimental determination of the stress–strain curves of specimens under partial loading, full unloading and repeated loading, a gradual accumulation of plastic strain was revealed for all considered thermoplastics. A finite element model for testing standard tensile specimens has been developed and validated. As a result of validation, multilinear isotropic hardening material law was identified for all investigated thermoplastics. Measured mechanical properties of porous thermoplastics were compared with properties declared by the manufacturer for the original raw material.

KEYWORDS

thermoplastics • polyacrylonitrile-co-butadiene-co-styrene • polycarbonate • polyetherimide • digital engineering mechanical properties • finite element method

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Introduction

In modern mechanical engineering, competitiveness is increasingly driven by the development of advanced materials and their corresponding manufacturing processes. The integration of polymer materials with 3D-printing technology enables the tailoring of unique mechanical properties to meet stringent design limitations on chemistry, weight, volume, and stiffness, which are paramount in aerospace and medical applications [1]. While specific material grades and chemical additives expand the applicability of polymers, they also necessitate detailed performance validation under operational conditions – a requirement effectively addressed through digital engineering technology [2].

3D-printing makes it possible to effectively use the provided volume, ensuring the requirements for strength and rigidity. At the same time, it changes the microstructure of the material and thus transforms the original isotropic material into anisotropic, due to the formation of porosity or orientation of polymer chain fragments [3]. 3D-printing of

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thermoplastics changes their physical and mechanical properties, which complicates the prediction of macroscopic reactions of constructures manufactured in such way [4].

It is necessary to note the advantage of thermosetting polymers in terms of the absence of such preconditions for the formation of anisotropy at the micro level due to another manufacturing technology – chemical polymerization.

While the physical, mechanical, and thermal properties of various thermoplastics are well-documented in general reviews [5,6], data for specific material grades – particularly those processed via additive manufacturing remain incomplete. Expanding the database of mechanical properties for various materials is valuable for the scientific and engineering community. 3D-printing significantly alters the properties of the original polymer feedstock. For example, in the article [7], it is shown that the building orientation of a part leads to a change in mechanical properties. Article [8] shows the effect of the layer stacking pattern during 3D-printing on the strength properties. The change in mechanical properties is explained by a different way of forming cavities at the micro level. In addition, for some high-molecular-weight polymers, manufacturing by 3D-printing is accompanied by orientation of polymer chain fragments, leading to the appearance of orthotropic mechanical properties at the macro level. However, the mechanical properties of a part are determined not only by its building orientation during manufacturing by 3D-printing. For example, article [9] shows the effect of various 3D-printing parameters on mechanical properties. In particular, the effect of the following parameters has been studied: layer thickness, thread width, filling density, layer orientation, printing speed and filling structure. The effect of 3D-printing parameters on mechanical properties has been studied not only for homogeneous specimens but also for heterogeneous specimens. Article [10] shows the effect of the infill percentage density and the different printing speed on the tensile properties. Special attention is paid to the effect of non-uniform temperature distribution during 3D-printing on mechanical properties. Article [11] shows the effect of the layer thickness, printing speed and the nozzle temperature on the mechanical properties. Article [12] is devoted to the study of the effect of non-uniform temperature distribution in the workpiece on the mechanical properties of specimens – individual parts of the workpiece. It has been determined that an important factor affecting the mechanical properties of thermoplastics is the time-dependent spatial temperature distribution during 3D-printing. Conversely, heating above the glass transition temperature can anneal these stresses, highlighting the complex relationship between thermal conditions and final mechanical properties.

The methodology of experimental and numerical determination of mechanical properties of standard specimens is well presented in the literature. Article [13] presents the results of experiments which are required for determination of the rheological material model and mechanical properties of standard specimens. Studied material represents a mixture of two types of thermoplastics in different proportions. Article [14] is devoted to the study of the effect of the building orientation of the part during manufacturing by laser stereolithography technology. The possibilities for achieving the best mechanical properties were investigated. In article [15], the mechanical properties of standard specimens of titanium alloy were studied experimentally and numerically using a finite element analysis software system.

This paper is devoted to the experimental and numerical study of the mechanical properties of standard (ISO 527-2:2025) specimens [16], which were manufactured by 3D-printing for specific thermoplastics certified in accordance with ISO 10993–4:2017 [17], namely: ABS–M30i [18,19], PC–ISO [20,21], Ultem 1010 resin [22–24]. Today, one of the methods for identifying the porosity of specimens is scanning electron microscopy of the cross-section of the surface [25,26]. This article studies mechanical properties of thermoplastics with voids and pores formed due to 3D-printing. These defects have been identified by cross-sectional scanning electron microscopy for all considered thermoplastics [27]. The ratio of voids (voids and pores) for ABS-M30i, PC–ISO and Ultem 1010 resin constitute 0.7 (~ 14), 0.4 (~ 20) and 3 (~ 20) % respectively.

Materials and Methods

The object of study is standard (ISO 527-2:2025) specimens, which were manufactured by 3D-printing from thermoplastics certified by standard ISO 10993–4:2017. In particular, the following thermoplastics were considered: polyacrylonitrile-co-butadiene-co-styrene (ABS–M30i, Stratasys Ltd.), polycarbonate (PC–ISO, Stratasys Ltd.) and polyetherimide (Ultem 1010 Resin, Stratasys Ltd.). Detailed information about the manufacturing of the considered thermoplastics, as well as their physical, chemical and surface properties have been presented in [27].

The tensile specimen was designed based on a standard geometry, the key dimensions of which are illustrated in Fig. 1(a). In accordance with this sketch, a full-scale geometric model of the specimen was developed (Fig. 2(b)) using a computer-aided design system SolidWorks (Dassault Systèmes SE). Based on this geometric model, 12 specimens of each considered thermoplastics were 3D-printed (Fig. 1(c)) using a 3D-printer Stratasys Fortus 450 mc (Stratasys Ltd.). Tensile tests were performed on thermoplastic specimens with a working area of 60 mm length, 5.9 mm width, and 3 mm thickness, in accordance with ISO 527-2:2025. Testing was conducted under standard ambient conditions using two Shimadzu universal testing machines (UTMs): a 5 kN AG–Xplus HS equipped with a pantograph and a 50 kN AG–50kNXD with a screw-type clamps. A constant crosshead speed of 1 mm/min was applied, and strain was measured by GL38 extensometer. The cyclic loading tests for mechanical hysteresis analysis (load-unload cycles down to 0.5 MPa) were exclusively performed on the 50 kN screw-type clamp machine, as this test configuration was not feasible with the pantograph clamp system.

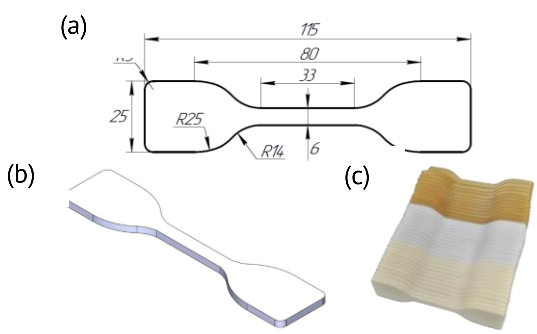

Fig. 1. Specimens: (a) sketch with relevant dimensions in mm; (b) geometric model; (c) 3D-printed specimens

Results and Discussion

Experimental part

An experimental study of the mechanical properties was conducted for standard (ISO 527-2:2025) thermoplastic specimens in the presence of porosity caused by 3D-printing. The following grades of thermoplastics certified in accordance with ISO 10993-4:2017 were considered: ABS–M30i (polyacrylonitrile-co-butadiene-co-styrene), PC–ISO (polycarbonate), Ultem 1010 resin (polyetherimide). Thermoplastics ABS-M30i and PC-ISO could be considered as isotropic materials [18,20], while thermoplastic Ultem 1010 resin is characterized by orthotropy of mechanical properties [22]. Tests for thermoplastic Ultem 1010 resin were conducted in XZ print orientation [22]. Tensile tests were conducted for determination of the mechanical properties in accordance with standard for tensile testing methods of plastics using the machine shown in Fig. 2.

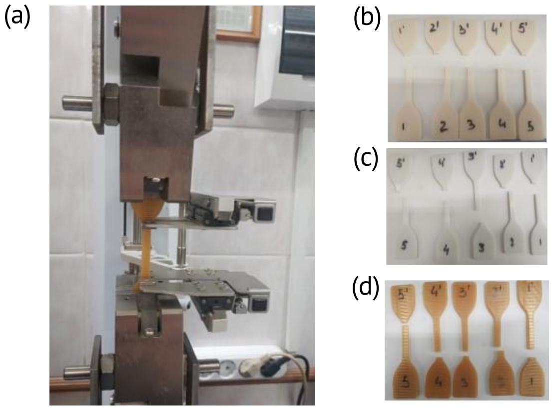

Fig. 2. Photographs of the: (a) tensile testing machine; (b) ABS–M30i specimens; (c) PC–ISO specimens; (d) Ultem 1010 resin specimens

As a result of experiments, stress–strain curves were determined, as well as the elastic modulus, tensile strength and elongation at break, which are given in Table 1. Mechanical properties of all considered thermoplastics are presented in comparison with VESTAKEEP i4 3DF [28] (polyetheretherketone), which is used today in endoprosthetics.

Table 1. Mechanical properties of thermoplastics

Thermoplastic	ABS-M30i	PC-ISO	Ultem 1010 resin	VESTAKEEP i4 3DF
Elastic modulus, MPa	2 400 [18]	2 000 [20]	3 040 [22]	3 500 [28]
Elastic modulus (experiment), MPa	2 203 (-8.2 %) Sd 38	2 094 (+4.7 %) Sd 165	3 257 (+7.1 %) Sd 92	–
Tensile strength, MPa	36 [18]	57 [20]	79.2 [22]	94 [28]
Tensile strength (experiment), MPa	28.4 (-21.1 %) Sd 0.3	49 (-14 %) Sd 0.3	88.6 (+11.9 %) Sd 4	–
Elongation at break, %	4 [18]	4 [20]	4 [22]	5 [28]
Elongation at break (experiment), %	7.7 (+92.5 %) Sd 1.1	5.3 (+32.5 %) Sd 0.2	4.35 (+8.8 %) Sd 0.4	–

As shown in Table 1, the experimentally determined elastic modulus for all studied 3D-printed thermoplastics correlates well with manufacturer datasheet values. The values of the experimentally determined elastic modulus for all considered thermoplastics correlate with the data sheet, in contrast to the other properties of these materials. A mechanical hysteresis was constructed for the identification of an adequate rheological model for all considered thermoplastics (Fig. 3).

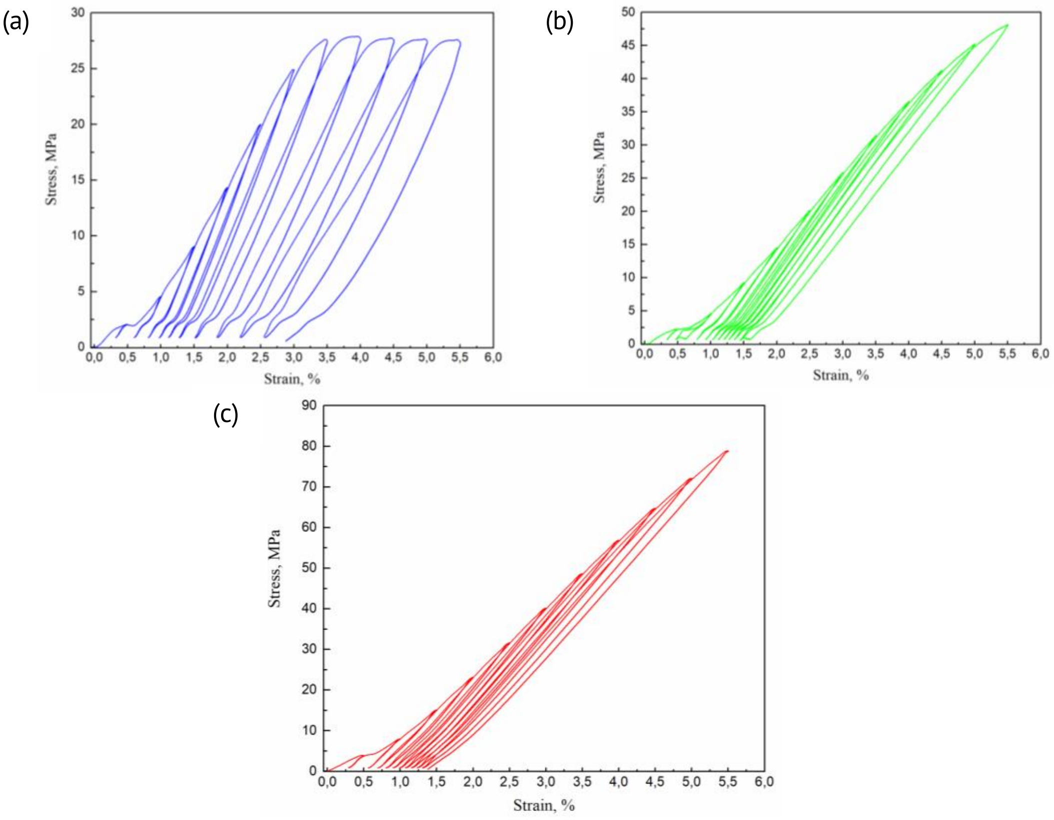

Fig. 3. Experimental stress–strain curves of investigated thermoplastics: (a) ABS-M30i; (b) PC–ISO; (c) Ultem 1010 resin

The experimentally determined tensile strength values for ABS–M30i and PC–ISO are lower than the values presented in data sheets. It is well explained by the presence of the porosity at micro level, which appears due to manufacturing by 3D-prining. This physical phenomenon has been confirmed by scanning electron microscopy of the cross section [27]. In contrast, Ultem 1010 Resin exhibited a less pronounced but opposite trend, which may be partly explained by the orthotropic nature of its feedstock [22]. Coupled with the technological parameters of 3D-printing, it led to a slight strengthening of the material.

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For all considered thermoplastics, an increase in the elongation at break is observed by comparison with data sheets. It is illustrated by the yield plateau on the stress–strain curves. As a result of the analysis of the stress–strain curves in combination with the loops of mechanical hysteresis, all investigated thermoplastics are prone to gradual accumulation of plastic strain under increasing load (Fig. 3).

Numerical part

Also, a numerical study of the mechanical properties of the considered thermoplastics was conducted using the SIMULIA Abaqus/Standard (Dassault Systèmes SE) finite element analysis software system [29–31]. Figure 4(a) shows a finite element model of a standard (ISO 527-2:2025) thermoplastic specimen, which contains about 10^4 linear finite elements (finite element type C3D8R). Figure 4(b) shows a boundary conditions imposed on the model. One edge of the specimen is assumed to be rigidly fixed in clamps, while displacements in the longitudinal direction were applied to the second edge of the specimen.

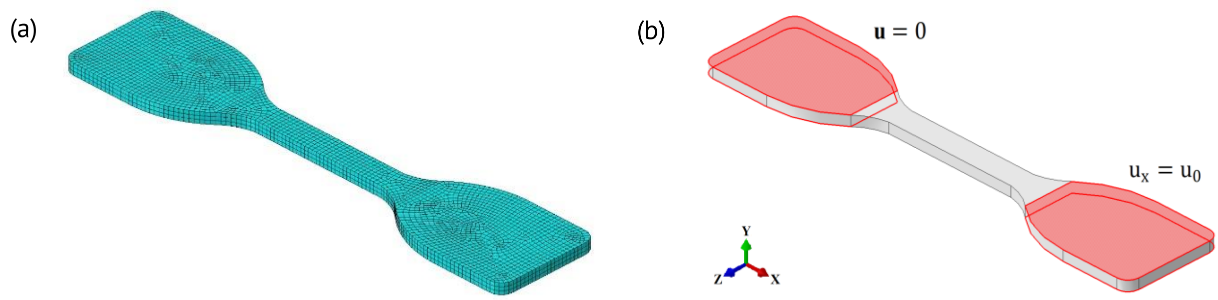

Fig. 4. Computational model of a specimen: (a) finite element model; (b) boundary conditions imposed on the model

An elastic-plastic material model (plastic material model) was chosen to describe the rheological behavior of the considered thermoplastics. The numerical values of the parameters for the multilinear isotropic hardening material law (Table 2) were iteratively identified in accordance with the experimentally determined stress-strain curves.

Table 2. Numerical values of the multilinear isotropic hardening material law

ABS-M30i		PC-ISO		Ultem 1010 resin	
Plastic strain	**Stress, Pa**	**Plastic strain**	**Stress, Pa**	**Plastic strain**	**Stress, Pa**
0	$1.3 \cdot 10^7$	0	$1 \cdot 10^7$	0	$2 \cdot 10^7$
0.0005	$2.1 \cdot 10^7$	0.001	$2 \cdot 10^7$	0.001	$3 \cdot 10^7$
0.0015	$2.5 \cdot 10^7$	0.002	$2.5 \cdot 10^7$	0.002	$4 \cdot 10^7$
0.002	$2.6 \cdot 10^7$	0.004	$3.2 \cdot 10^7$	0.0035	$5 \cdot 10^7$
0.0025	$2.7 \cdot 10^7$	0.0055	$3.6 \cdot 10^7$	0.0055	$6 \cdot 10^7$
0.003	$2.75 \cdot 10^7$	0.0085	$4.05 \cdot 10^7$	0.0085	$7 \cdot 10^7$
0.004	$2.8 \cdot 10^7$	0.0135	$4.55 \cdot 10^7$	0.013	$8 \cdot 10^7$
0.008	$2.85 \cdot 10^7$	0.022	$4.9 \cdot 10^7$	0.019	$8.8 \cdot 10^7$

As a result of the numerical simulation of stretching a standard specimen, the stress-strain state was determined. The following characteristics were determined by finite element method: displacement (Fig. 5(a)), von Mises stress intensity (Fig. 5(b)) and plastic strain (Fig. 5(c)).

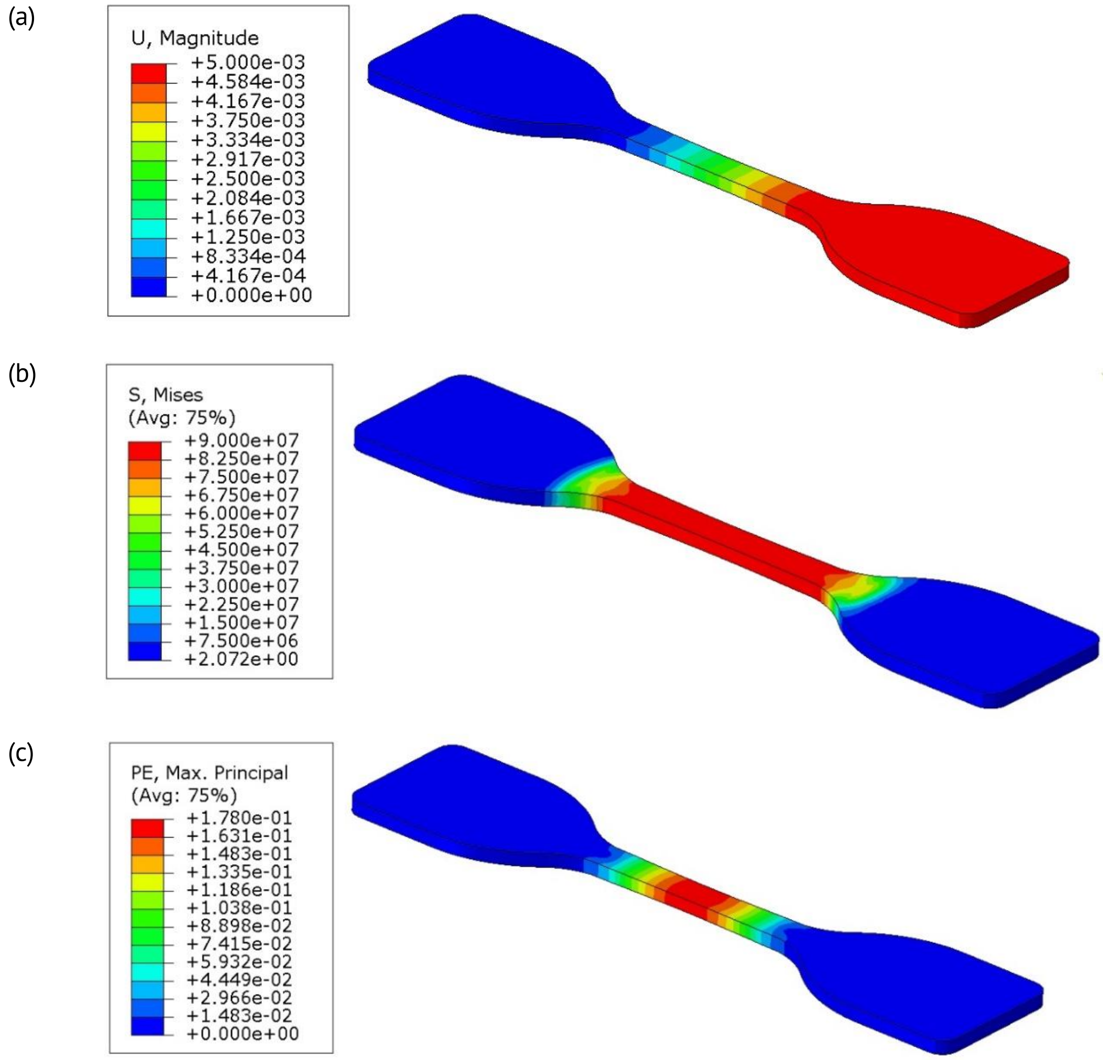

Fig. 5. Stress-strain state of specimen (in case of the Ultem 1010 resin): (a) displacement; (b) von Mises stress intensity; (c) Plastic strain

Modeling was conducted on 6 core desktop computer with Intel i7 CPU and 16 Gb RAM. As a result of the multivariant solution for all considered thermoplastics, numerical values of the multilinear isotropic hardening material law (Table 2) were identified. Thus, the developed digital model for tensile testing of specimens was validated (Fig. 6). The data in the first row of Table 2 delineate the transition from the conditionally safe (elastic) region to the plastic flow zone. In other words, it is safety to say that stress values below 13, 10 and 20 MPa for ABS−M30i, PC−ISO and Ultem 1010 resin thermoplastics respectively do not lead to the formation of plastic strain. Stresses above these values result in the accumulation of plastic strain, which is confirmed by the presence of a mechanical hysteresis loop (Fig. 3).

Comparison of results

As a result of the experimental and numerical study of mechanical properties, stress-strain curves were determined for all considered thermoplastics (Fig. 6). The numerical values of the multilinear isotropic hardening material law for all considered thermoplastics were determined in such a way that the numerical stress-strain curves lie in the middle between the experimental curves whole over the entire deformation.

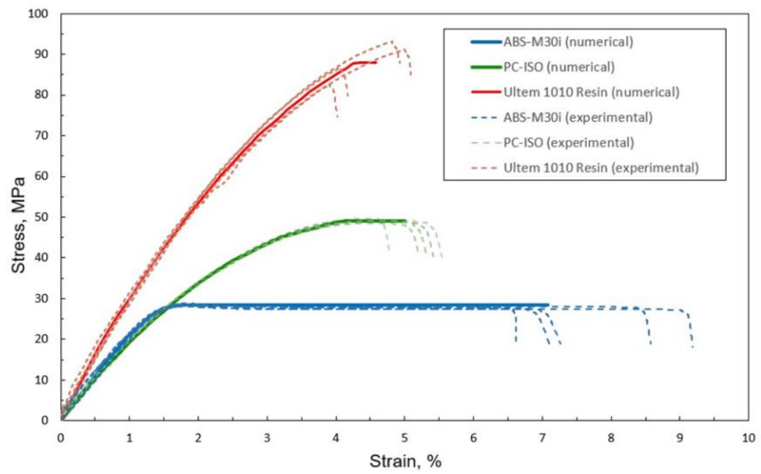

Fig. 6. Experimental and numerically calculated stress-strain curves of investigated thermoplastics: ABS– 30i, PC–ISO, Ultem 1010 resin

From all considered thermoplastics ABS–M30i has the lowest tensile strength. All things being equal, this circumstance does not allow ABS–M30i to be recommended for critical and loaded components of mechanical systems in terms of ensuring strength requirements. It should also be noted that ABS–M30i exhibits explicit yield plateau after exceeding a relative deformation of 1.8 % up to a relative deformation of 7.7 %, which corresponds to failure.

In turn, PC–ISO has the most nonlinear stress–strain curve compared to other considered thermoplastics. PC–ISO has a significantly higher tensile strength compared to ABS–M30i, but it enters the plastic flow zone earlier than considered thermoplastics. As a result of which, it contributes to the formation and accumulation of irreversible deformations and defects during operation under cyclic loads. All things being equal, this circumstance does not allow PC–ISO to be recommended for parts and structures with durability requirements.

From all considered thermoplastics Ultem 1010 resin has the most tensile strength and rigidity. Mechanical properties of Ultem 1010 resin are close to cortical bone tissue and VESTAKEEP i4 3DF (polyetheretherketone), which is used today in endoprosthetics. The difference in the rheological behavior of the studied thermoplastics is directly related to their chemical composition and structure, which is implicit indicated by the value of the glass transition [27]. The lower the glass transition of polymer material, the more explicit the plastic behavior is. These features make it possible to consider Ultem 1010 resin as a promising material for usage in mechanical systems with requirements for strength and durability.

Conclusions

In the presented research paper, the mechanical properties of certified (ISO 10993– 4:2017) thermoplastics ABS–M30i (polyacrylonitrile-co-butadiene-co-styrene), PC–ISO (polycarbonate) and Ultem 1010 Resin (polyetherimide) were investigated using standard (ISO 527-2:2025) specimens, which were manufactured by 3D-printing. The mechanical properties of thermoplastics with voids and pores formed due to 3D-printing have been studied. For all considered thermoplastics stress–strain curves were experimentally constructed, as well as a mechanical hysteresis. Based on the results of the experimental study, an elastic-plastic material model was chosen to adequately describe the rheological behavior of polymer materials. As a result of the numerical study of mechanical properties, a validated digital model for tensile testing of a specimen was developed. Based on the results of the numerical study, the numerical values of the multilinear isotropic hardening material law were identified for all considered thermoplastics. Also, measured mechanical properties of porous thermoplastics after 3D-printing were compared with the properties for the original raw material.

An important scientific result of this article consists in the identification of a rheological model and its numerical parameters for all considered thermoplastics: ABS– M30i, PC–ISO and Ultem 1010 resin. The suggested validated multilinear isotropic hardening material law can be used as part of a digital twin of mechanical systems in various industries. For example, to develop a digital twin of the skeleton-endoprosthesis system for large human joints. As part of further research of mechanical properties of the investigated thermoplastics, several areas of scientific and practical importance can be denoted, for example: durability research; determination of the mechanical properties of wet thermoplastics (for example in saline solution); investigation of the effect of temperature on mechanical properties.

CRediT authorship contribution statement

Ilya A. Keresten: writing – review & editing, writing – original draft, conceptualization, investigation, supervision, data curation; **Pavel B. Pirozhnikov**: writing – review & editing, investigation, supervision; **Ian S. Suranov**: writing – original draft, data curation; **Erofeev A. Daniil**: investigation; **Alexey G. Titov**: conceptualization.

Conflict of interest

The authors declare that they have no conflict of interest.

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