# Selected mechanical properties of polymer models manufactured by hybrid rapid prototyping

**Mariusz Dębski**[1), *)] (ORCID ID: 0000-0002-4889-7633), **Piotr Niesłony**[2)] (0000-0001-8776-8458), **Bogdan Kozik**[1)] (0000-0002-8111-6456), **Jadwiga Pisula**[1)] (0000-0002-3197-9528)

DOI: https://doi.org/10.14314/polimery.2024.11.2

**Abstract:** A hybrid technology for manufacturing parts from polymer materials (ABS, PLA) was developed, combining the layered extrusion method and casting under reduced pressure. The silicone mold (used in the pressure casting method) was replaced with a thin-walled shell (with the geometry of the manufactured element) made by the layered extrusion method. Then, in the vacuum casting process, this shell was filled with a chemically cured polyurethane resin. Tensile and flexural properties of the developed models were tested. The possibility of reducing the anisotropy of additively manufactured parts mechanical properties was confirmed.

**Keywords:** additive technologies, polymer materials, hybrid technologies, vacuum casting.

## Wybrane właściwości mechaniczne modeli polimerowych wytworzonych metodą hybrydowego szybkiego prototypowania

**Streszczenie:** Opracowano hybrydową technologię wytwarzania części z materiałów polimerowych (ABS, PLA), łączącą metodę wytłaczania warstwowego i odlewania pod obniżonym ciśnieniem. Formę silikonową (stosowaną w metodzie odlewania ciśnieniowego) zastąpiono cienkościenną formą (o geometrii wytwarzanego elementu) wykonaną metodą wytłaczania warstwowego. Następnie w procesie odlewania próżniowego forma ta została wypełniona żywicą poliuretanową utwardzaną chemicznie. Zbadano właściwości mechaniczne przy rozciąganiu i zginaniu opracowanych modeli. Potwierdzono możliwość zmniejszenia anizotropii właściwości mechanicznych części wytwarzanych metodą przyrostową.

**Słowa kluczowe:** technologie przyrostowe, materiały polimerowe, technologie hybrydowe, odlewanie próżniowe.

Additive methods are classified using different division criteria. Additive Manufacturing (AM) processes can be divided into three separate groups: Rapid Prototyping (RP), additive manufacturing of prototype machine parts, as well as finished, fully functional products that can be used as load-bearing or structural elements of machines and devices (RM - Rapid Manufacturing), and additive tool manufacturing (RT – Rapid Tooling) [1, 2].

According to ISO/ASTM 52900:2015, additive manufacturing technologies can be divided into seven general categories. This classification is based on the basic principle of operation and includes volume photopolymerization (VPP), material jetting (MJ), binder jetting (BJ), powder bed fusion (PBF), material extrusion (MEX), directed energy deposition (DED), and sheet lamination (SL). Furthermore, depending on the type of base material used, RP techniques can be divided into three different categories, i.e. powder-based, liquid-based, and solid-based [3].

Over the past few years, additive manufacturing has undergone a significant evolution, both in terms of the variety of methods and materials used. This dynamic change has contributed to the wide application of these technologies in many industries and fields. Currently, additive manufacturing is used in the automotive, aerospace, medical, construction, military and food industries, among others [4-7]. In particular, the medical industry has begun to experiment intensively with the production of tissues, organs, and cellular structures using additive technologies. This has enabled the creation of complex, three-dimensional biological structures that can be used in regenerative medicine and in the treatment of various diseases [8, 9]. In addition, additive technologies significantly shorten the time needed to develop tooling and reduce the costs associated with

[1)] Department of Machine Design, The Faculty of Mechanical Engineering and Aeronautics, Rzeszow University of Technology, Al. Powstańców Warszawy 12, 35-959 Rzeszów, Poland.
[2)] Faculty of Mechanical Engineering, Opole University of Technology, ul. Prószkowska 76, 45-758 Opole, Poland.
[*)] Author for correspondence: m.debski@prz.edu.pl

making prototypes. This makes the process of designing and implementing new products more effective and economical, which is particularly important in dynamically developing industries [10, 11].

One of the most popular and widespread 3D printing technologies is the layered extrusion method. This technique involves the gradual application of layers of plasticized material, which allows the creation of three-dimensional objects of various shapes and sizes. The layered extrusion method allows the use of a wide range of polymer materials, including composite materials and thermoplastics, which are commonly used in injection molding technology [12, 13]. Due to the low costs of consumables, the layered extrusion method is often used to build functional prototypes and in small-scale production. It allows for fast and cheap production of components, which is particularly useful in the testing and development phase of new products. Additionally, the ease of use and availability of devices makes this technology popular among both professionals and hobbyists. However, the layered extrusion method also has some limitations. One of the main problems is the relatively high anisotropy of the manufactured parts, which means that their mechanical properties vary depending on the direction of the material layers [14-16]. In addition, the production of larger parts can be time-consuming, and the accuracy of the models is limited due to the layer stepping effect, which results in high surface roughness. In addition, the need for support structures that must be removed later, as well as problems with material shrinkage, can affect the quality and strength of the final product. Despite these limitations, the layered extrusion method remains one of the most versatile and accessible 3D printing technologies, constantly finding new applications in various industries, from engineering and architecture to medicine and education [17, 18].

Vacuum casting (VC) due to its low manufacturing costs (cheaper materials and tools) is a widely used method of manufacturing tooling, especially in small-batch and unit production, allowing for a shorter time to market for new products [19, 20]. This method involves vacuum casting of thermosetting epoxy, polyester, polyurethane resins or wax in molds made of silicone resins, as well as composites of resins with metal powders [21, 22]. The most commonly used tools in the VC process are silicone rubber molds produced by the Room Temperature Vulcanization (RTV) method by encapsulating the pattern. The principle of the RTV method is to reproduce the geometry of the reference model (usually obtained by one of the RP methods) by enclosing it with two-component silicone rubbers [23]. The RTV process is usually carried out under atmospheric pressure, which is associated with the risk of air in the mold in the area of direct contact with the surface of the base model, which in turn causes a significant decrease in the accuracy of the vacuum casting process [24, 25]. However, in order to ensure high precision of surface quality reproduction and dimensional and shape conditions of the reference model, immediately after pouring the technical silicone, a vacuum degassing process is carried out, which allows for the removal of gas bubbles formed during the mixing of silicone components [26, 27].

Additive manufacturing technologies will enable the production of complex elements that are impossible or uneconomical to produce using other methods, but they still face challenges that create barriers to their further use in engineering fields. The main limitations of 3D printing technology are the change in the strength of the generated elements in relation to the orientation of the model in the device's working chamber.

The anisotropy of materials of parts printed using the layered extrusion method has a significant impact on their strength [28]. This results directly from the manufacturing direction, which is perpendicular (normal) to the object's parting plane. In the classic FDM method, the manufacturing direction remains unchanged during the model construction. The strength of the elements decreases in the load directions similar to the direction of the model construction. Therefore, it is necessary to arrange the parts in the workspace of the device in such a way that the loads run parallel to the direction of the longest contour fibers, and at the same time are not parallel to the manufacturing direction [29, 30, 31]. On the other hand, the dimensional accuracy, especially in the case of rotational elements, is the highest in the direction of the model construction (vertical axis). Greater accuracy in the vertical direction also results from the lack of the need to use support structures. In the case of manufacturing solids of revolution in the horizontal plane, where the generated supports contact the surface of the part, the model is distorted, and thus the dimensional accuracy is reduced.

An important factor causing material anisotropy, especially mechanical anisotropy, is insufficient interlayer adhesion (between successively built layers), which is a consequence of the lack of melting of the source material [32]. The extruded material quickly cools from the melting temperature to the temperature of the printer chamber, which causes internal stresses responsible for the weak bond between two adjacent paths. Therefore, it is reasonable to say that the strength of the object at the layer boundaries is the lowest [33, 34].

The solution to the problems related to material anisotropy and dimensional accuracy limitations in the layered extrusion method is the development of a hybrid technology for manufacturing prototypes and functional machine parts, based on the combination of the layered extrusion method with low-pressure casting. Therefore, the authors developed a manufacturing method based on a thin-walled coating made by the layered extrusion method, which is a framework for obtaining a real model, which is created by filling the thin-walled coating with a chemically cured polyurethane resin using the technology of casting under reduced pressure. An example

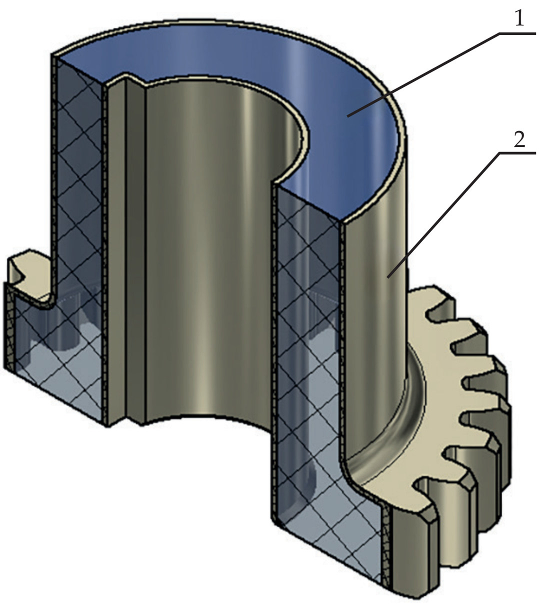


**Fig. 1. Part of a gear clutch made by layered extrusion and low-pressure casting: 1 – filling with chemically cured resin, 2 – thin-walled element**

model is shown in Fig. 1. Moreover, tensile and flexural properties of the developed models were tested.

## EXPERIMENTAL PART

### Materials

The samples were manufactured using ABS and PLA from Spectrum Filaments (Pęcice, Poland), processed using MEX technology, and vacuum-cast chemically cured resins PR2000, PR700, and PR1819 (Synthene, Pont-Sainte-Maxence, France). These resins are two-component polyurethane compositions designed for rapid prototyping and short-series production of parts. The first criterion for selecting the selected resins was their physical properties similar to thermoplastics such as ABS, PC/PMMA. Based on the material cards, it can be assumed that chemically cured resins have greater strength than additively processed thermoplastics. Another criterion related to the selection of polyurethane resins for vacuum casting was the parameter defined as "life time", which ranged from 6 to 19 minutes depending on the type of resin. In addition, polyurethane resins are characterized by low shrinkage and no volatile substances. The process of producing samples using hybrid technology was carried out on a Schüchl UHG-400 Easy pressure casting machine (Brunnen, Switzerland).

### Samples preparation

Manufacturing machine elements solely by the layered extrusion method is associated with certain limitations, including a low ratio of mechanical strength to dimensional and shape accuracy for axisymmetric parts. In connection with this, a hybrid technology for manufacturing elements was developed, which consists in combining the layered extrusion method with casting under reduced pressure. The silicone mold (used in the casting method under reduced pressure) is replaced by a thin-walled shell (with the geometry of the manufactured element) made by the layered extrusion method. Then, in the vacuum casting process, the coating is filled with a chemically hardened resin. In the case of parts intended for additive manufacturing using hybrid technology, the main design process does not change, but it is necessary to take into account the modification of this process due to the final product, which is a thin-walled coating. The methodology describing the production of machine parts using hybrid technology can be divided into four basic stages:

1. Design of the part based on which the three-dimensional geometry constituting the basic element of the final product:

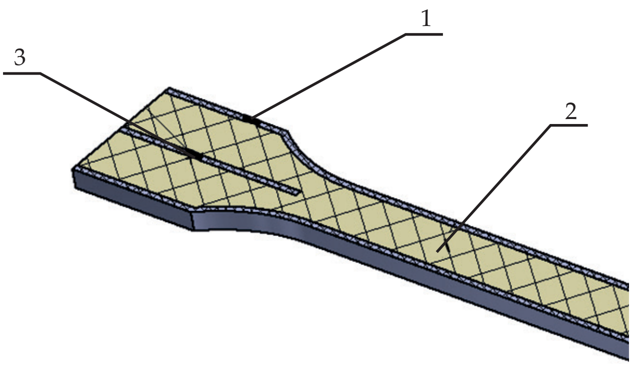


**Fig. 2. Sample for tensile properties: 1 – thin-walled coating, 2 – chemically cured resin, 3 – rib**

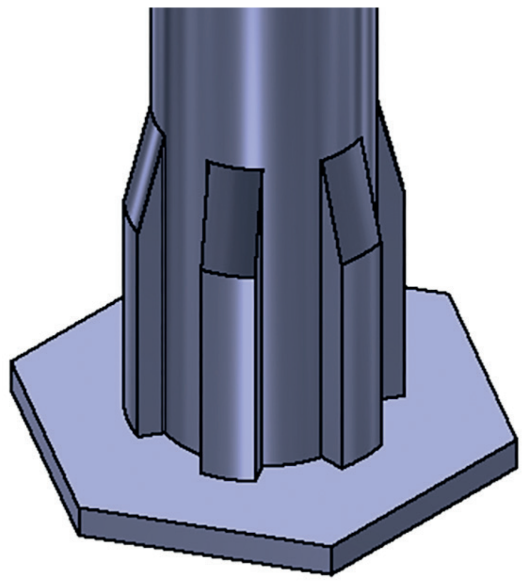

**Fig. 3. Support structure of the slender element**

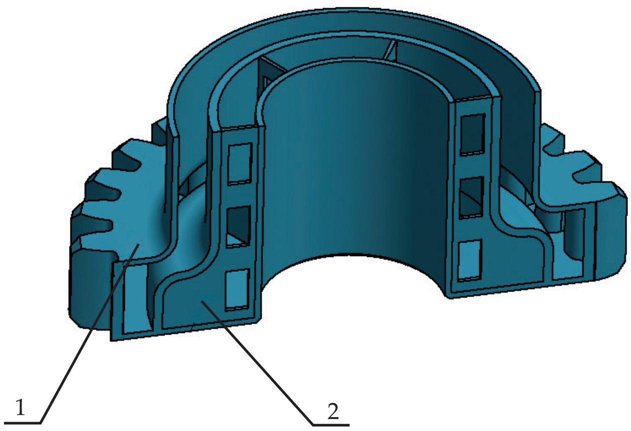


**Fig. 4. Gear clutch: 1 – thin-walled coating, 2 – rib**

– development of a 3D CAD solid model, taking into account: allowances for mechanical processing (finishing, cutting off flood systems), dimensional tolerances, polymer material used, parameters and limitations of the incremental process, arrangement of parts in the working chamber of the device,

– development of a thin-walled coating taking into account the guidelines depending on the geometry of the object: for parts that are not solids of revolution, manufactured additively in the horizontal plane, ribs should be placed inside the geometry, which will allow obtaining the upper outer shell of the manufactured model while maintaining dimensional and shape accuracy (Fig. 2),

– for slender elements manufactured vertically in relation to the device's working platform, feet (which will

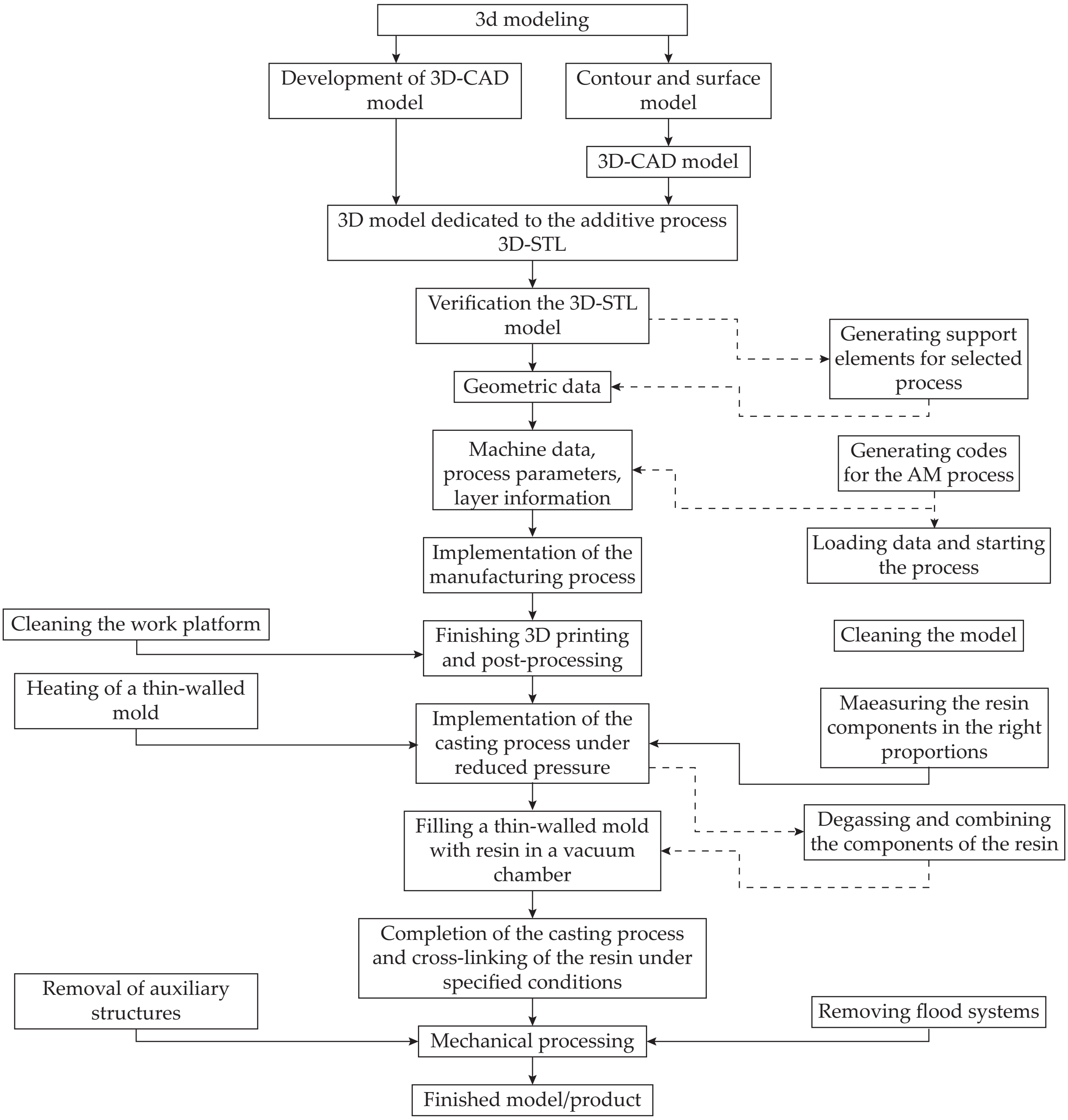


**Fig. 5. Hybrid part manufacturing process steps**

be mechanically removed in the final process) should be designed to prevent the material from detaching from the device's working platform (Fig. 3),

– for axisymmetric elements manufactured vertically in relation to the device's working platform, a core with a polygonal cross-section (hexagon, octagon) is recommended as the filling shape, which is related to the impossibility of rotating the thin-walled shell in relation to the filling due to insufficient adhesion between the materials,

– for fillings with a core cross-section that is circular, it is recommended to place inserts that block the possibility of rotation between the core and the shell,

– for a part that will be filled with two resins, the minimum thickness of the wall separating the resins should be taken into account or it should be additionally connected to the model shell by making holes to allow the resin to flow (Fig. 4),

– development of flooding systems connected to the part or taking into account the places where they will be installed,

– data export to STL format,

– data processing or repair (triangle mesh verification).

2. Production of thin-walled coating and possible pouring systems using the layer extrusion method:

– model geometry conversion, placing the model in the virtual chamber of the device, setting the parameters of the incremental process, taking into account: no generation of support structures in places intended to be filled with chemically cured resin, parameter control to limit air gaps,

– generating code for the printing device,

– starting the process,

– post-processing.

3. Filling the coating with chemically hardened resin in the vacuum casting process under reduced pressure and carrying out heat treatment of the part:

– heating of the thin-walled coating,

– measuring the components of the chemically cured resin in the appropriate proportions,

– degassing and combining the resin components in a vacuum chamber,

– filling of thin-walled shell,

– heating the part filled with chemically curable resin under conditions specified for the resin used.

4. Machining of parts after the process is completed.

Taking into account the presented methodology for manufacturing machine parts using hybrid technology, it can be noted that in the case of points three and four, the manufacturing of parts depends mainly on the guidelines provided by the resin manufacturer and on the low-pressure casting method. However, at the design stage, the parameters of preheating of the coating and cross-linking of the resin should be taken into account in relation to the softening temperature of the polymer material. An inappropriately selected polymer material can cause deformation of the thin-walled coating, and consequently, deterioration of the dimensional and shape accuracy of the manufactured part. The individual phases of the hybrid manufacturing process are shown in Figure 5.

The production of test samples using hybrid technology (in accordance with the developed production methodology) should begin with the production of a thin-walled coating (Fig. 6). The test samples were designed in a way that allows them to be connected to the potting systems. This approach allows for vacuum casting of several samples in one cycle.

The chemically cured resins were cast according to the recommendations presented in the product cards. The initial casting process for all three resins was as follows: measuring the two resin components in the appropriate proportions into containers, heating the thin-walled coating to the temperature 70°C, placing the thin-walled coating and containers with resin components in a vacuum chamber (Fig. 7).

The next step of the procedure depended on the type of chemically cured resin. In the case of PR2000 resin, its components were left in vacuum conditions for 10 min and then mixed together. The mixing process lasted 2 min, after which a thin-walled coating was poured. In order to cure the resin, the sample was heated in an oven for 60 min at a temperature of 70°C.

The PR700 resin components and the heated thin-walled coating were placed in a vacuum for 10 min (similar to PR2000). The combined components (isocyanate and

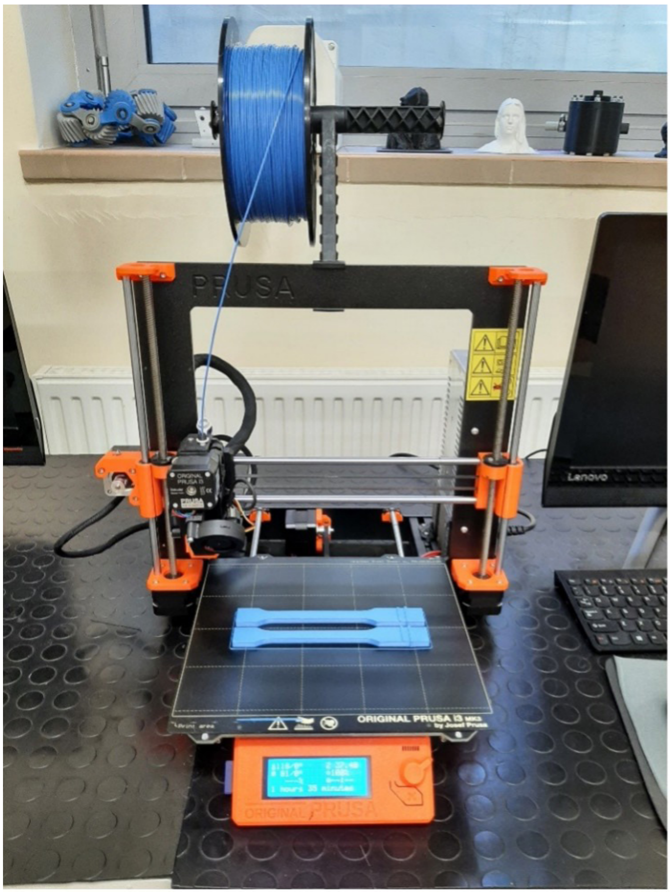


**Fig. 6. 3D-printing of test samples**

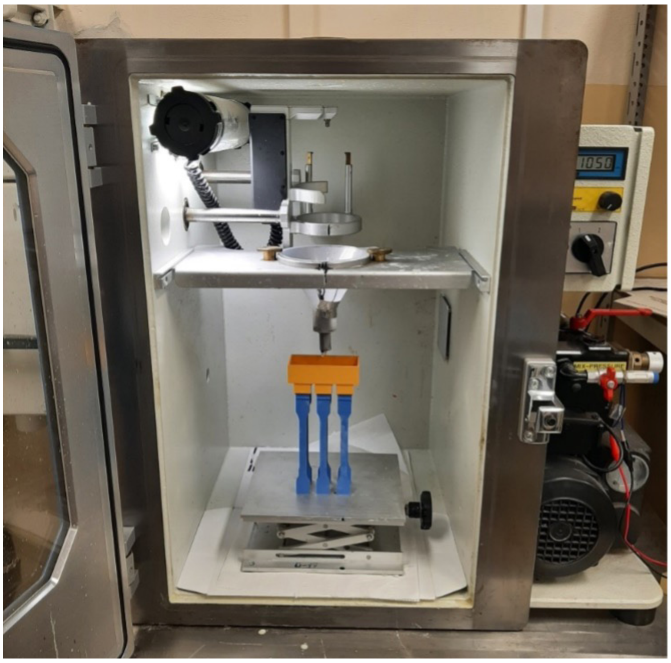

**Fig. 7. Vacuum casting chamber**

polyol) were mixed for 1 min, after which the chamber pressure was set at 100 hPa and the coating was poured, which was then baked at 70°C for 45 min. The samples were post-cured at 120°C for 120 min.

The PR1819 resin components were mixed for 3 min after a ten-minute air bubble removal process and then poured into a thin-walled shell. The samples were heated for 180 min at 70°C and for 16 h at 100°C.

The samples obtained using hybrid technology were mechanically removed from the potting systems and auxiliary structures. No leaks of polyurethane resin were observed on the surface of the samples due to the discontinuity of the thin-walled coating produced by the layer extrusion method.

### Methods

Mechanical properties tests were carried out for samples manufactured using three different technologies: layer extrusion, low-pressure casting and the developed hybrid technology combining the layer extrusion method with low-pressure casting. Samples manufactured exclusively using the layer extrusion method were made in vertical and horizontal positions relative to the device's working platform. On the other hand, thin-walled molds for the hybrid technology were made in a horizontal position relative to the device's working platform.

The test samples obtained by layer extrusion and thin-walled molds were made on a Prusa i3 MK3 printer (Prague, Czech Republic). The printing process for all models was characterized by the following basic parameters: alternating paths at angles of 45º and 135º, density of the internal structure filling – 100%, two contour lines, plastic layer height 0.2 mm.

The processing parameters for PLA and ABS copolymer are presented in Table 1.

**T a b l e 1. Process parameters for PLA and ABS materials**

| Material | PLA/PLA PRO | ABS |
|---|---|---|
| Head temperature, °C | 210 | 255 |
| Work table temperature, °C | 60 | 100 |
| Chamber | Open | Close |

The reference models for the silicone mold (Vacuum Casting technology) were made on the Object Eden 260V printer (Stratasys, Eden Prairie, Minnesota, USA) operating in the PolyJet technology. The optically active resin RGD720 from Stratasys (Eden Praire, Minnesota, USA) was used as the model material. The samples were prepared in the HQ (High Quality) mode with a layer height of 0.016 mm. The supports were generated in accordance with the selected version - glossy, in which the support material occurs only where it is necessary, and the surfaces that do not have contact with the supports are glossy. After the printing process was completed, the support structures were rinsed in the pressure chamber of a water washer. The support material was removed using a stream of heated water.

Tensile and flexural properties were measured using Instron 5967 testing machine (Norwood, MA, USA) according to PN-EN ISO 527-2 and PN-EN ISO 178, respectively. The crosshead speeds for tensile and flexural tests were 5 and 2 mm/min, respectively. The gage length for tensile tests was 50 mm.

## RESULTS AND DISCUSSION

Figures 8 and 9 present the comparisons of tensile strength and elongation at break of the samples.

Samples made by layered extrusion from ABS copolymer in a vertical position relative to the device's working platform had the lowest tensile strength (18.6 MPa). This is related to the directional action of the load directed parallel to the structure of the model layers, for which the adhesive form of connection of successive layers of plasticized material is characterized by low strength. In the case of samples made in a horizontal position, a twofold increase in strength and the highest elongation at break can be observed. The increase in stresses and deformations results from the arrangement of the model in the working chamber of the device. The sample made in a horizontal position has two contour outlines (the material threads are arranged in accordance with the direction of loading) and alternating filling at angles of 45° and 135°, which causes a complex state of stresses inside the object that is not conducive to sample delamination.

In the case of ABS samples filled with PR700 and PR1819 chemically cured resins, an increase in tensile strength

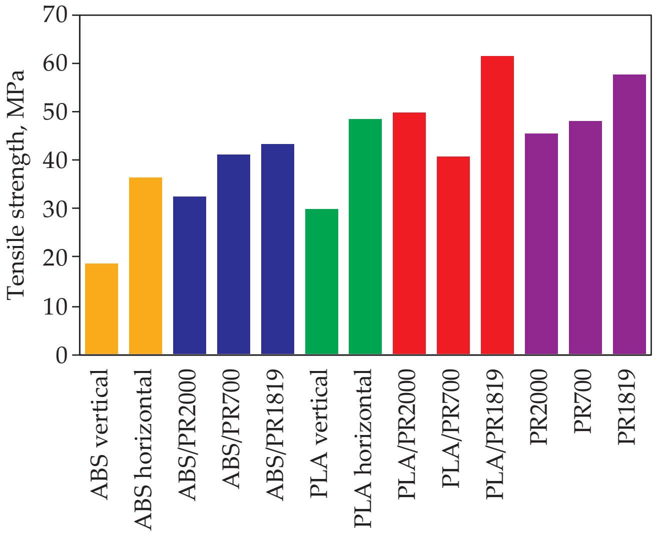


**Fig. 8. Tensile strength of the samples**

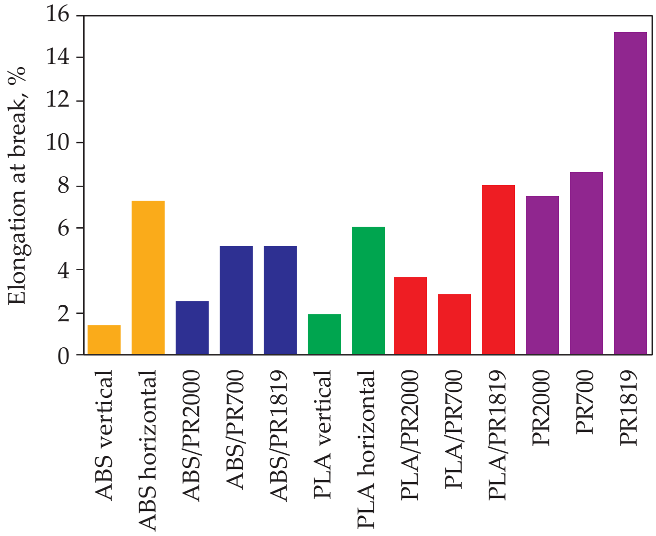


**Fig. 9. Elongation at break of the samples**

can be observed compared to samples made only by the layer extrusion method. After exceeding the conventional yield point, the tensile strength in both cases increases to 41.2 MPa and 43.4 MPa, respectively. The models filled with PR2000 resin were characterized by lower strength compared to ABS samples produced horizontally to the working platform of the device.

Samples made of PLA (similarly to those made of ABS) in a vertical position relative to the working platform of the device were characterized by the lowest tensile strength and the lowest elongation at break. The tensile strength of the samples was 29.9 MPa. In the case of samples placed horizontally, an increase in tensile strength can be observed, which was 48.6 MPa.

Samples filled with PR2000 resin had similar strength to the polylactide test models in a horizontal position relative to the device's working platform. For samples filled with PR1819 resin, the tensile strength was 61.4 MPa, while the average elongation at break was 8%. It is important to note that in the case of samples filled with PR700 resin, the tensile strength was lower than in the case of samples made of PLA in a horizontal position, which indicates low adhesive properties of the chemically cured resin used in relation to PLA.

Experimental studies have shown that samples made with hybrid technology record an increase in tensile strength by about 75–133% compared to samples made of ABS copolymer in a vertical position relative to the device's working platform. In the case of PLA, this increase was about 36–105%. Samples filled with PR700 and PR1819 resins, the thin-walled form of which was made of ABS copolymer, had tensile strength 13% and 19% higher than samples made in the horizontal position, while in the case of PR2000 resin, a decrease in tensile strength by 11% can be observed. In the case of a thin-walled mould made of PLA, an increase in the tensile strength by 2% and 26% was observed for the research models filled with PR2000 and PR1819 resins, while a decrease in tensile strength by 16% was observed for the PR700 resin.

Comparing the samples made in hybrid technology with the base material (chemically cured resins) for a thin-walled mould made of ABS copolymer, a decrease in tensile strength of 72–85% can be observed. In the case of a thin-walled mould made of PLA, the decrease in tensile strength compared to the base material is about 15% for the PR700 resin, while samples filled with PR2000 and PR1819 resins record an increase of about 10% and 6%.

The deformation at break of the samples made using the hybrid technology is lower in comparison to the research models made in a horizontal position in relation to the working platform of the device and cast using the VC method, apart from the polylactide sample filled with PR1819 resin for which an increase in the deformation value by approx. 31% can be observed in relation to the samples in a horizontal position.

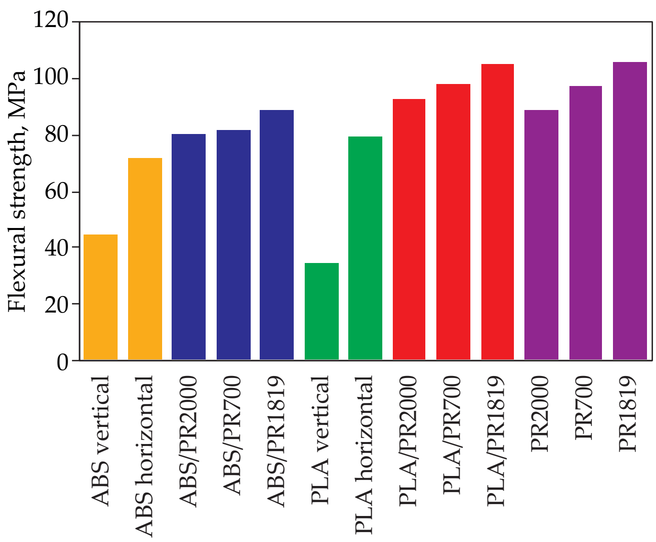


**Fig. 10. Flexural strength of the samples**

Figure 10 presents flexural strength at maximum load for the samples. It can be observed that flexural strength of the samples manufactured using hybrid technology increased by 80–98% compared to the models manufactured from ABS copolymer vertically in relation to the device's working platform and by 12–24% for the samples in a horizontal position. In the case of a thin-walled mould made of PLA, an increase in flexural strength of 166–202% was observed for samples filled with chemically curable resins, compared to the vertical position, and of 17–33% compared to the horizontal position for samples produced by layer extrusion.

Flexural strength of samples whose thin-walled mould was made of ABS copolymer is about 83–90% of the value of the base material (chemically cured resins). In the case of PLA mould, flexural strength is similar to samples made by casting under reduced pressure (±4% of the base value).

## CONCLUSIONS

A hybrid technology combining the layered extrusion method with the low-pressure casting technology was developed. It was confirmed that the strength of the elements produced by the layered extrusion method decreased in the load directions similar to the model construction direction. Moreover, differences were observed between the samples made by the hybrid technology and the low-pressure casting method. The tensile strength of the samples made by the hybrid technology was similar to the base material. However, the elongation at break, depending on the resin used, was 190-290% higher than that of the samples made by the hybrid technology. It can therefore be concluded that the production of samples using the technology combining MEX and VC affects the decrease in the plastic deformation capacity of the core of samples made of chemically cured resin. This is due to the adhesion of the processed materials and the formation of notches at their connections.

***Authors contribution***

M.D. – conceptualization, methodology, writing-original draft, supervision, writing-review and editing, validation; P.N. – conceptualization, methodology, writing-original draft, validation; B.K. – investigation, formal analysis, software, visualization; J.P. – investigation, software, visualization.

***Funding***

The research received no external funding.

***Conflict of interest***

The authors declare no conflict of interest.



## REFERENCES

[1] Kordowska M., Musiał W., Stefanowicz K.: *Autobusy: technika, eksploatacja, systemy transportowe* **2014**, *15(6)*, 158.

[2] Sęp J., Budzik G.: *Mechanik* **2015**, *12*, 169. https://doi.org/10.17814/mechanik.2015.12.581

[3] Kafle A., Luis E., Silwal R. *et al.*: *Polymers* **2021**, *13(18)*, 3101. https://doi.org/10.3390/polym13183101

[4] Dave H.K., Prajapati A.R., Rajpurohit S.R. *et al.*: *Rapid Prototyping Journal* **2020**, *26(1)*, 21. https://doi.org/10.1108/RPJ-01-2019-0003

[5] Long J., Gholizadeh H., Lu J. *et al.*: *Current Pharmaceutical Design* **2017**, *23(3)*, 433. https://doi.org/10.2174/1381612822666161026162707

[6] Prasong W., Muanchan P., Ishigami A. *et al.*: *Journal of Nanomaterials* **2020**, *2020(1)*, 8040517. https://doi.org/10.1155/2020/8040517

[7] Yadav D.K., Srivastava R., Dev S.: *Materials Today: Proceedings* **2020**, *26(2)*, 2089. https://doi.org/10.1016/j.matpr.2020.02.451

[8] Singh D., Singh R., Boparai K.S.: *Journal of Manufacturing Processes* **2018**, 31, 80. https://doi.org/10.1016/j.jmapro.2017.10.026

[9] Sun Y., Tian,W., Zhang T. *et al.*: *Materials and Design* **2020**, 185, 108239. https://doi.org/10.1016/j.matdes.2019.108239

[10] Leal R., Barreiros F.M., Alves L. *et al.*: *The International Journal of Advanced Manufacturing Technology* **2017**, *92*, 1671. https://doi.org/10.1007/s00170-017-0239-8

[11] Richardson M., Haylock B.: *Computer-Aided Design and Applications* **2012**, *9*, 33.

[12] Chacón J.M., Caminero M.A., García-Plaza E. *et al.*: *Materials and Design* **2017**, *124*, 143. https://doi.org/10.1016/j.matdes.2017.03.065

[13] Wu W., Geng P., Li G. *et al.*: *Materials* **2015**, 8(9), 5834. https://doi.org/10.3390/ma8095271

[14] García-Domínguez A., Claver J., Camacho A.M. *et al.*: *Materials* **2020**, 13(1), 28. https://doi.org/10.3390/ma13010028

[15] Li Q., Zhao W., Li Y. *et al.*: *Polymers* **2019**, *11(4)*, 656. https://doi.org/10.3390/polym11040656

[16] Mazzanti V., Malagutti L., Mollica F.: *Polymers* **2019**, *11(7)*, 1094. https://doi.org/10.3390/polym11071094

[17] Barrios J.M., Romero P.E.: *Materials* **2019**, *12(16)*, 2574. https://doi.org/10.3390/ma12162574

[18] Buj-Corral I., Domínguez-Fernández A., Durán-Llucià R.: *Materials* **2019**, *12(23)*, 3834.

https://doi.org/10.3390/ma12233834
[19] Kuo C.C., Chen W.-H., Lin Y.-X. *et al*.: *The International Journal of Advanced Manufacturing Technology* **2020**, *108*, 1509.
https://doi.org/10.1007/s00170-020-05508-2
[20] Kuo C.C., Wu M.-X.: *The International Journal of Advanced Manufacturing Technology* **2017**, *90*, 3775.
https://doi.org/10.1007/s00170-016-9755-1
[21] Kuo C.C., Qiu,W.K., Liu H.A. *et al*.: *The International Journal of Advanced Manufacturing Technology* **2019**, *105*, 1469.
https://doi.org/10.1007/s00170-019-04386-7
[22] Zhu X., Wang F., Ma D. *et al*.: *Metals* **2020**, *10(3)*, 299.
https://doi.org/10.3390/met10030299
[23] Frankiewicz M., Kobiela K., Kurzynowski T.: *Polymers* **2021**, *13(6)*, 874.
https://doi.org/10.3390/polym13060874
[24] Puerta P.V., Sanchez D.M., Batista M. *et al*.: *Journal of Manufacturing Processes* **2018**, *35*, 721.
https://doi.org/10.1016/j.jmapro.2018.08.033
[25] Rodríguez-González P., Robles Valero P.E., Fernández-Abia A.I. *et al*.: *Metals* **2020**, *10(8)*, 1090.
https://doi.org/10.3390/met10081090
[26] Oleksy M., Heneczkowski M., Oliwa R. *et al*.: *Polimery* **2014**, *59(9)*, 677.
https://doi.org/10.14314/polimery.2014.677
[27] Zhan S., Song J., Ding M. *et al*.: *Advances in Engineering Research* **2017**, *135*, 574.
https://doi.org/10.2991/iccte-17.2017.102
[28] Roberson D., Shemelya C.M., MacDonald E. *et al*.: *Rapid Prototyping Journal* **2015**, *21(2)*, 137.
https://doi.org/10.1108/RPJ-12-2014-0165
[29] Gnanasekaran K., Heijmans T., van Bennekom S. *et al*.: *Applied Materials Today* **2017**, *9*, 21.
https://doi.org/10.1016/j.apmt.2017.04.003
[30] Pepliński K. Czyżewski P. Górecki D. *et al*.: *Polimery* **2017**, *62(3)*, 198.
https://doi.org/10.14314/polimery.2017.198
[31] Prajapati H., Ravoori D., Woods R.L. *et al*.: *Additive Manufacturing* **2018**, *21*, 84.
https://doi.org/10.1016/j.addma.2018.02.019
[32] Aliheidari N., Christ J., Tripuraneni R. *et al*.: *Materials and Design* **2018**, *156*, 351.
https://doi.org/10.1016/j.matdes.2018.07.001
[33] Ngo T.D., Kashani A., Imbalzano G. *et al*.: *Composites Part B: Engineering* **2018**, *143*, 172.
https://doi.org/10.1016/j.compositesb.2018.02.012
[34] Shih C.-C., Burnette M., Staack D. *et al*.: *Additive Manufacturing* **2019**, *25*, 104.
https://doi.org/10.1016/j.addma.2018.11.005

*Received 10 X 2024.*
*Accepted 27 X 2024.*