Jacek BERNACZEK[1*] ORCID: 0000-0002-8942-092X; **Piotr CICHOSZ**[2] ORCID: 0000-0003-1026-298X

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[1] The Department of Mechanical Engineering, Faculty of Mechanical Engineering and Aeronautics, Rzeszow University of Technology, al. Powstańców Warszawy 12, 35-959 Rzeszów, Polska
[2] Proximo Aero Sp. z o.o., pl. Jana Kilińskiego 2, 35-005 Rzeszów, Polska
* Corresponding author: jacek.bernaczek@prz.edu.pl

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TESTING OF THE PROTOTYPE OF A ONE-WAY FUEL SYSTEM VALVE

BADANIA PROTOTYPU JEDNOKIERUNKOWEGO ZAWORU INSTALACJI PALIWOWEJ

***Summary**: The subject of the publication is the research of a prototype of a one-way fuel system valve manufactured using the additive technique. The valve design was developed in the CAD environment in the aspect of manufacturing the model using the additive technique. The models were subjected to numerical analysis of stress distribution using the finite element method FEM in order to confirm the dimensional, shape and material conditions. The manufacturing process was developed using the thermoplastic modeling technique FFF (Fused Filament Fabrication) from two commonly used model materials, i.e. PLA and ABS. The physical models were subjected to bench tests. Based on the numerical analysis of FEM and experimental tests based on the manufactured prototypes, the specified assumptions were confirmed.*

***Keywords**: the prototype of a one-way fuel system valve, numerical analysis of stress distribution, the finite element method FEM, thermoplastic modeling technique FFF, model materials, i.e. PLA and ABS*

Streszczenie: Przedmiotem publikacji są badania prototypu jednokierunkowego zaworu instalacji paliwowej wytwarzanego techniką przyrostową. Opracowano konstrukcję zaworu w środowisku CAD w aspekcie wytworzenia modelu techniką przyrostową. Modele poddano numerycznej analizie rozkładu naprężeń metodą elementów skończonych MES celem potwierdzenia uwarunkowań wymiarowo kształtowych i materiałowych. Opracowano proces wytwarzania techniką modelowania tworzywem termoplastycznym FFF (ang. *Fused Filament Fabrication*) z dwóch powszechnie wykorzystywanych materiałów modelowych, tj. PLA i ABS. Modele fizyczne poddano badaniom stanowiskowym. Na podstawie analizy numerycznej MES oraz badań doświadczalnych w oparciu o wytworzone prototypy potwierdzono sprecyzowane założenia.

Słowa kluczowe: prototyp jednokierunkowego zaworu instalacji paliwowej, numeryczna analiza rozkładu naprężeń, metoda elementów skończonych MES, technika modelowania tworzywem termoplastycznym FFF, materiały modelowe PLA i ABS

Introduction

The main assumption for the target design of the valve in question is to work for a wide range of fuels, including Jet A1, at temperatures from – 60°C and significantly lower weight than reference valves manufactured based on aluminum alloys [8, 9, 15]. Additionally, it is advisable to develop a valve body design for the hybrid manufacturing process, i.e. vacuum casting based on an additively manufactured base model [1, 11]. When considering the above, work was undertaken to develop a design solution that provides better strength properties in the aspect of manufacturing using the subject technique [3, 4, 5, 7]. A CAD design of the valve was developed and a numerical analysis of the stress distribution FEM was carried out [2, 6, 10, 12]. The models manufactured using the FFF technique from PLA and ABS materials were subjected to physical tests on a dedicated stand. The next step was to develop and analyze the test results [13]. The culmination of the work was the process of developing wax vacuum castings intended for the production of functional parts of the valve body from the target light metal alloy.

Valve body CAD design

In order to confirm the developed design assumptions for the production of the valve body, a complex design process was carried out in the CAD (Computer Aided Design) environment. The body in question was developed in two parts for the target research models – a condition directly resulting from the possibility of applying the internal elements of the valve. On the other hand, for the needs of the bench tests carried out as part of this work, the prototype was made according to the assembly, in its entirety. The models and its cross-section are presented in Figures 1 and 2.

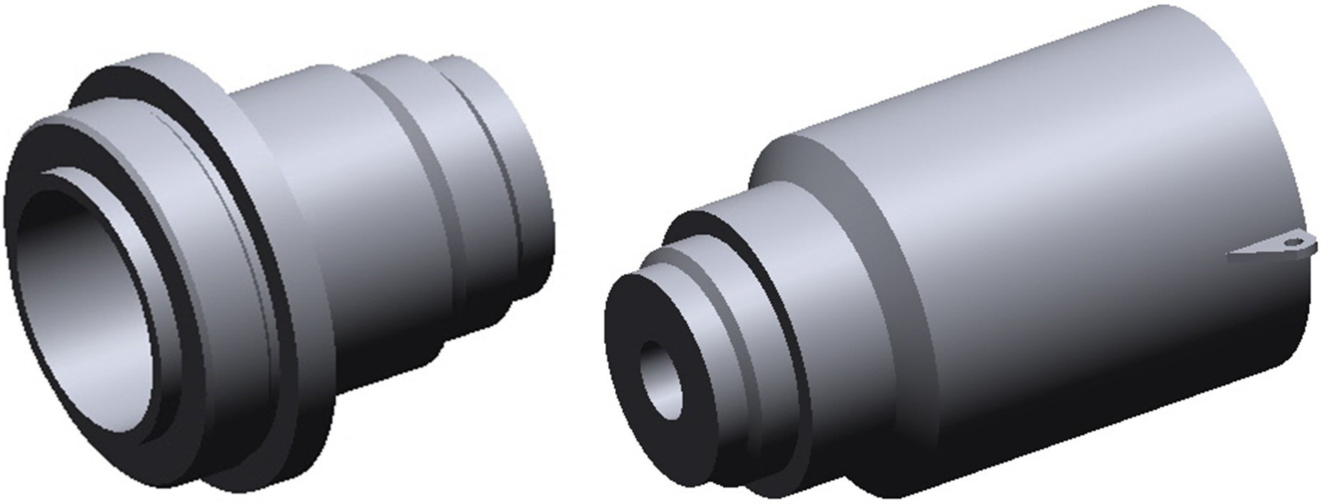

Fig. 1. 3D-CAD models of individual valve body parts

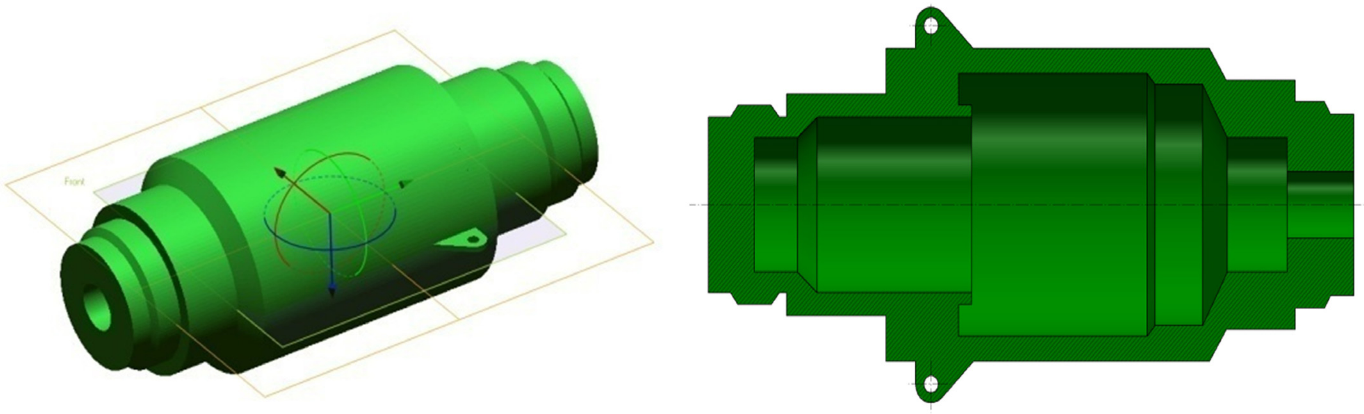

Fig. 2. 3D-CAD model and cross-section of the valve used in the printing process – assembly

The developed CAD models of the valve were verified for the possibility of producing prototypes using the FFF additive technique, i.e. taking into account the technological limitations of the thermoplastic modeling method for selected materials [1, 4, 13].

FEM analysis of valve body models

The developed CAD models of the valve body were used for strength analysis – numerical analysis of stress distribution using the finite element method (FEM) in Simcenter software. Simcenter software is used for finite element modeling and visualization of results. The program includes a full package of pre- and post-processing tools and supports a wide range of solutions for evaluating product performance. The subject analysis was carried out based on the material data declared by the manufacturer, including primarily Young's modulus and yield strength – for ABS: Young's modulus – 2400 [Mpa], yield strength – 43 [Mpa] and for PLA: Young's modulus – 2800 [Mpa], yield strength – 50 [Mpa]. The strength analysis of the valve was carried out by assigning the above-defined two types of materials to the CAD model: ABS and PLA. Based on the use of Simcenter software, two mounting methods were defined: at the valve inlet (together with the analysis conditions) and from both ends of the valves (together with the analysis conditions). The numerical model of the valve was loaded, in accordance with the previously defined conditions, with pressures of – 4, 10, 20 and 40 [MPa], respectively. Selected results of numerical tests are presented in Figures 3 and 4.

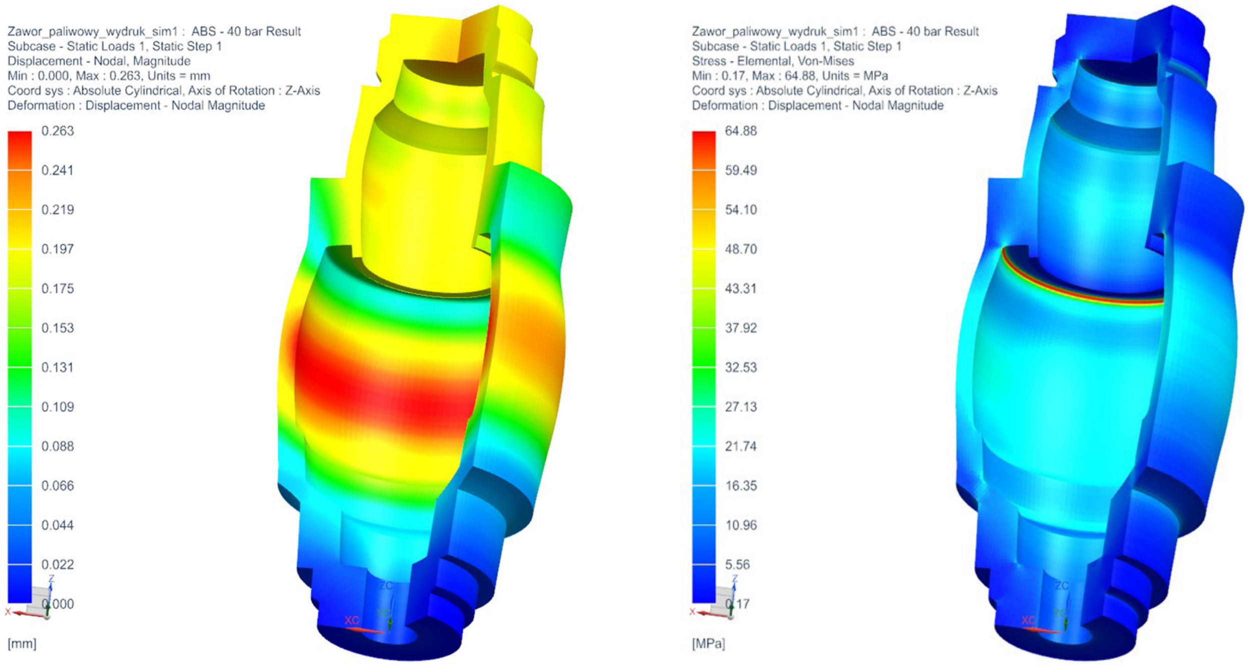

Fig. 3. FEM analysis results of the ABS valve – from the left displacement and Von-Mises stresses

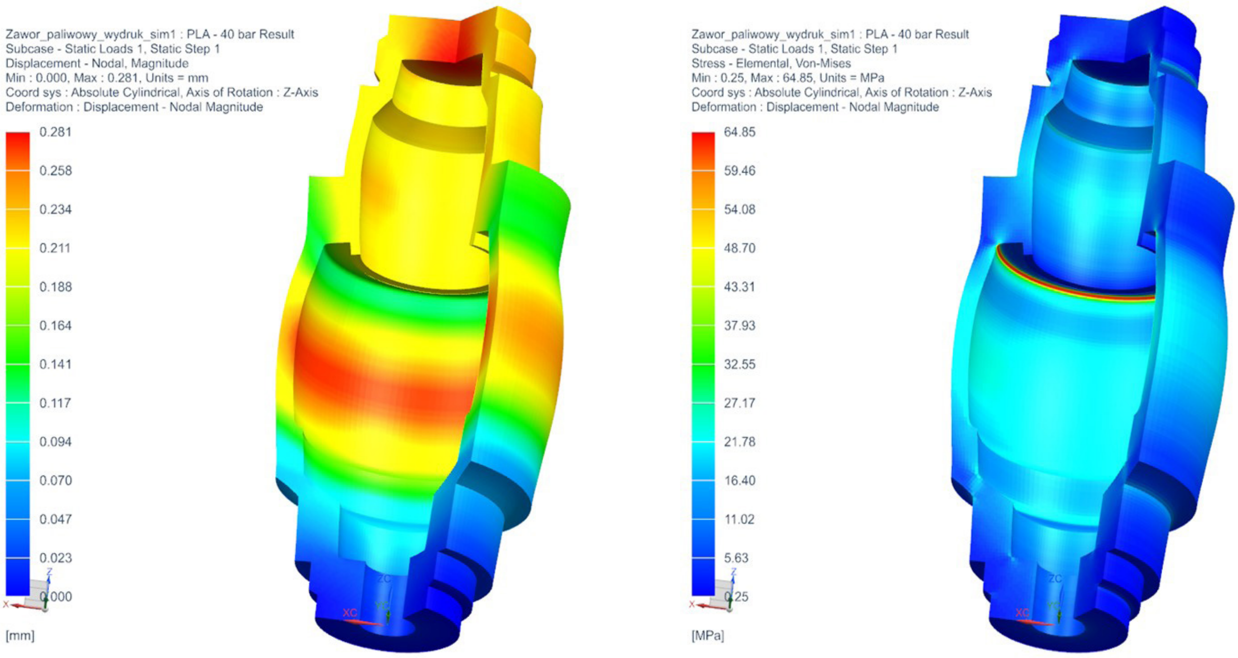

Fig. 4. Results of the FEM analysis of the PLA valve – from the left displacement and Von-Mises stresses

The FEM analysis allowed for determining the values of key parameters and characteristic areas – stress concentration, displacement and safety factor for selected materials [2, 6, 10, 12].

Additive manufacturing of valve bodies

Valve prototypes were made of ABS and PLA materials using the FFF additive technique [1, 13]. Models were produced in two orientations – horizontal and vertical in order to conduct comparative analysis in the process of destructive bench tests. The first step was to develop the parameters of the manufacturing process and define key data in the tool software. Based on the discussed procedure, valve body models were produced (Fig. 5).

The models were subjected to finishing treatment consisting in removing the support structure characteristic of the selected technique.

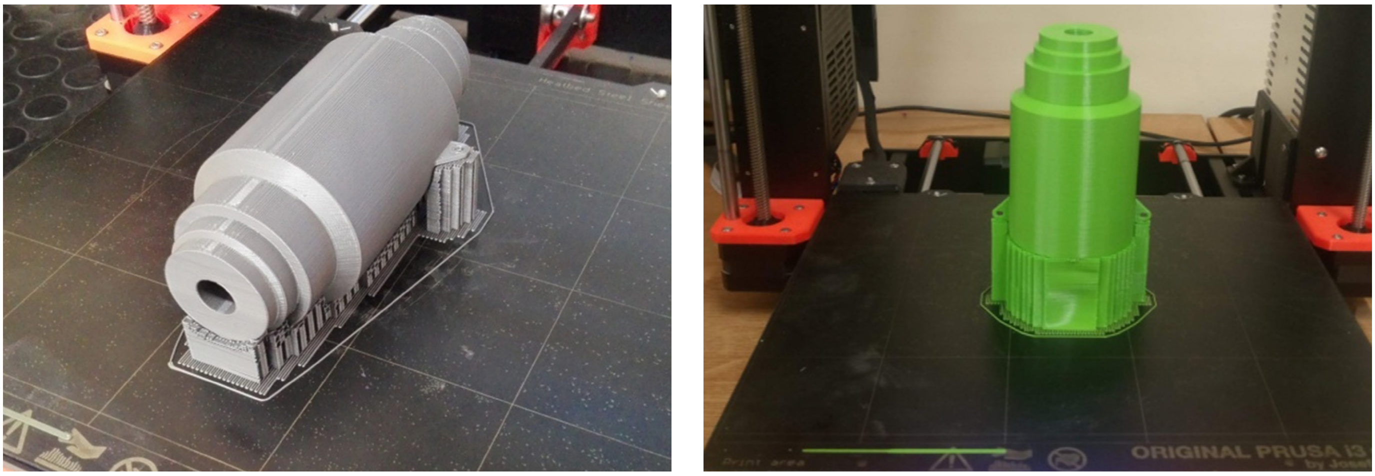

Fig. 5. Valve models – from the left, the PLA model in horizontal orientation and the ABS model in vertical orientation

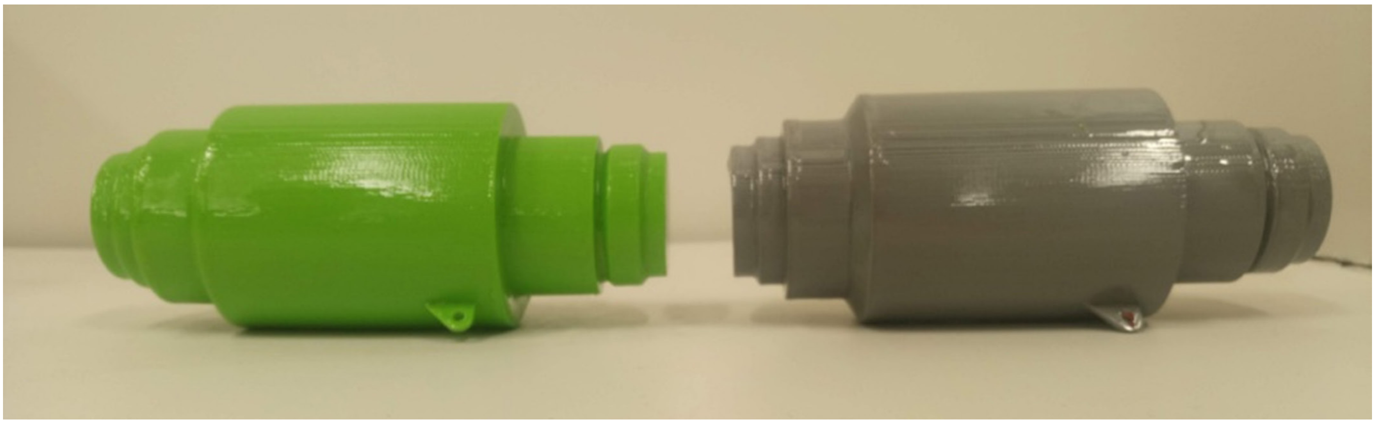

Fig. 6. Valve models after the impregnation process

One set of models was additionally impregnated with a single-component colorless polyurethane varnish to seal and eliminate surface defects resulting from the FFF additive technology (Fig. 6).

The additional impregnation procedure in question enables the production of silicone molds in the VC (Vacuum Casting) vacuum forming process based on FFF reference models. The produced polyurethane coating protects the model against the action/soaking of technical silicone in a liquid, uncured state, thus enabling the model to be demolded without damaging the mold surface. At the same time, better surface quality is obtained, which is also important in the hybrid manufacturing process - using additive techniques and vacuum casting [14]. The selected results of the comparative analysis of the surfaces of base models and impregnated models are shown in Figure 7.

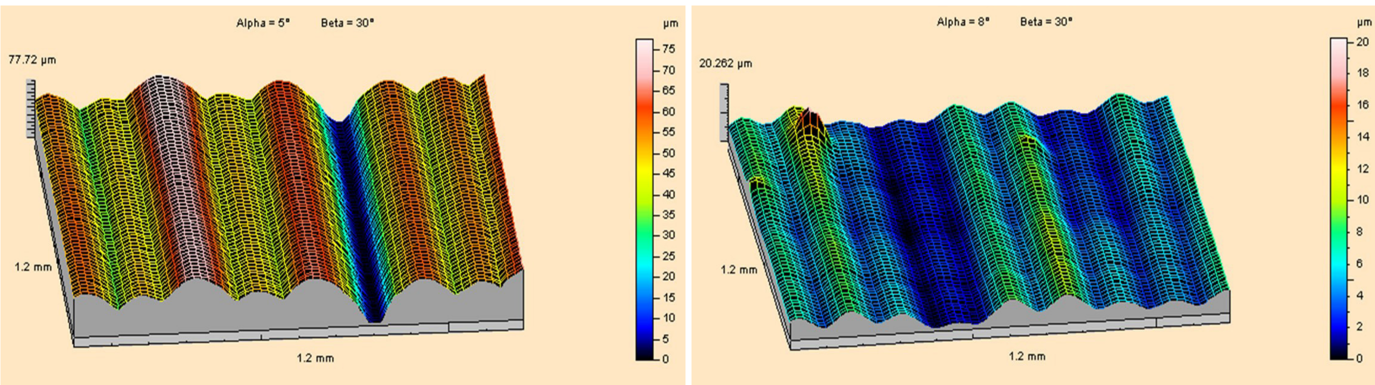

Fig. 7. Surface topography of the ABS valve model – from the left, the basic and impregnated

Silicone moulds made based on impregnated valve models can be used to produce models from technical casting wax, and these in turn can be used to produce valves using the lost-model method in casting.

Destructive bench testing of valve bodies

The tests were carried out on a test stand of the author's design equipped with a high-pressure pump (up to 40 MPa). Diesel oil was used as the working medium. The valve bodies were plugged in the additive manufacturing process (modified CAD design). The working medium was supplied using a threaded intake system. The stand was protected by a housing structure made of 18 mm thick PMMA plate. The selected photos from the research process are shown in Figure 8.

The summary results of the destructive bench tests of all variants of valve models are presented in Table 1.

The development and analysis of the research results indicate a higher strength of the PLA thermoplastic material compared to ABS. Additionally, an increase in pressure was found for the two materials during the destruction of valve prototypes for the horizontal orientation of the models in the additive manufacturing process and variants with a polyurethane coating. It was observed that the valve prototypes cracked in the areas of connecting the successive layers of the model material in both orientations in the FFF process (Fig.9).

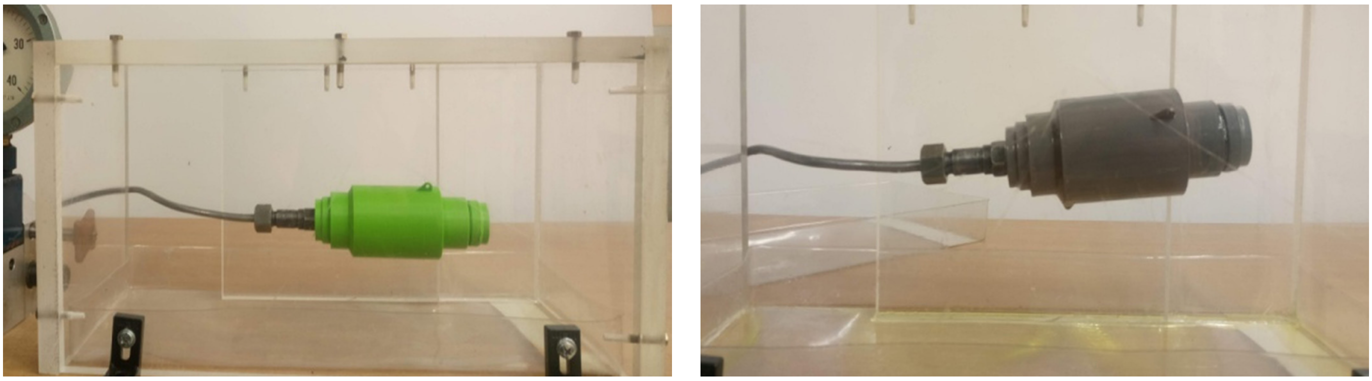

Fig. 8. Destructive bench testing process – from the left, the ABS valve and the PLA valve

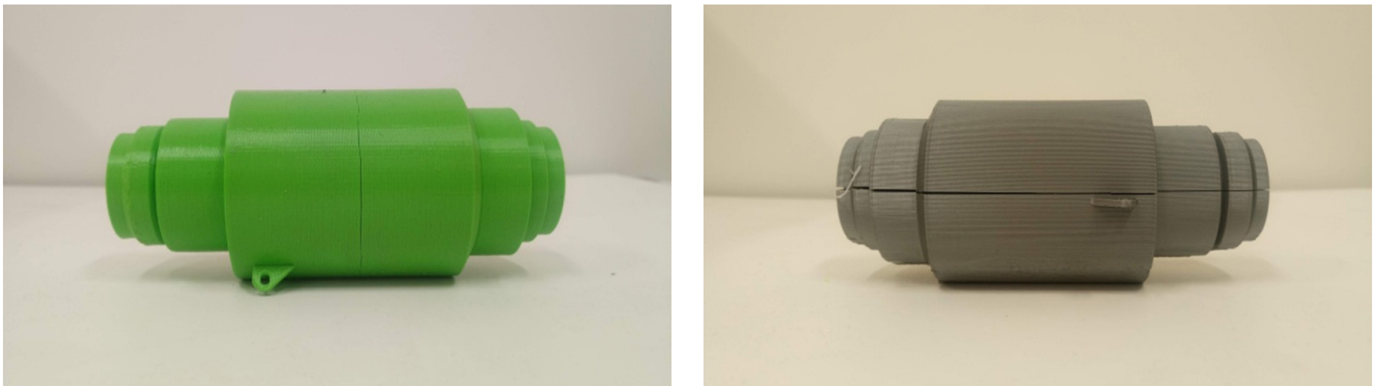

Fig. 9. Valve prototypes after the destructive bench testing process – from the left, the ABS valve and the PLA valve

Table 1. Results of destructive tests of valve models

Fuel system one-way valve	Max. pressure – valve without impregnation	Max. pressure – impregnated valve – with polyurethane coating
ABS valve in horizontal orientation	4 MPa	4.5 MPa
PLA valve in horizontal orientation	5 MPa	5.5 MPa
ABS valve in vertical orientation	3.5 MPa	4 MPa
PLA valve in vertical orientation	4.5 MPa	5 MPa

The area of cracks – delamination under the influence of pressure in places where layers are connected is characteristic of additively manufactured models. Subsequently applied layers in the FFF technique are connected with each other using the increased temperature of the previous layer and, consequently, the ongoing process of stabilization of the thermoplastic material. Therefore, the area in question is most exposed to load.

Production of valve body models using vacuum casting technique

BThe impregnated prototype of the subject body of the one-way fuel system valve, intended for the implementation of research works, was made in the next stage of the research using a hybrid technique in the process of vacuum forming in silicone molds. The body was manufactured based on the construction of two parts described at the beginning of this article. Manufacturing prototype elements in silicone molds is classified as an indirect rapid prototyping technique. The process is a stage of a hybrid manufacturing technique. In this method, a silicone mold or matrix is created based on reference models and, on the principle of a negative, reflects the geometry of the prototype. The base model can be made using additive techniques, in this case – the FFF technique. A silicone mold is a tool used to make elements from casting waxes as well as to make castings from plastics (polyester resins, epoxy polyurethanes). Silicone processing tools are suitable for making short series of products from several to several dozen pieces – the quantity is determined primarily by geometry, the advancement of which directly affects the process of damaging the mold – its surface – under the influence of demolding of finished castings. Additionally, chemical and thermal impact during the prototype production process causes deterioration of the dimensional and shape accuracy of silicone molds.

Valve body castings made from tool wax in individual silicone molds are shown in Figure 10.

The developed wax vacuum castings of valve body elements will be intended for the production of functional body parts from the target light metal alloy at the stage of further research works.

Final conclusions

Based on the research work carried out, the final conclusions were drawn:

1. The developed CAD design enables the valve to be manufactured using a hybrid method based on additive techniques and vacuum forming.
2. Numerical analysis of stress distribution based on the finite element method FEM for the selected materials and loading conditions ensures the strength of the valve structure in question according to the adopted assumptions.
3. The valve according to the developed design can be manufactured using additive technology – thermoplastic modeling from ABS and PLA materials.
4. Experimental (destructive) tests of additively manufactured valves carried out on the basis of the author's research stand equipped with a high-pressure pump resulted in obtaining very good strength results ensuring the possibility of using the valves in question in target applications.
5. The impregnation process of additively manufactured valve models increased their strength – based on the experimental studies, the strength of individual valves was found to increase by at least 10% compared to non-impregnated additively manufactured models.
6. Impregnation of the models resulted in a change in the surface topography – the conducted tests showed a significant improvement in the surface quality of the impregnated models (several-fold improvement of selected topography parameters).
7. The improvement of the surface quality of FFF models resulting from the impregnation process simultaneously ensures a favorable change in the properties (surface quality)

Fig.10. Wax castings of valve body parts

of the target castings resulting from the hybrid production of valves in the vacuum forming process using tool wax and, consequently (after making a casting mould using the lost wax method and the casting process) of the final product – a metal alloy casting.

8. Impregnation of FFF valves facilitates the process of vacuum forming using technical silicone – it protects the reference model against silicone soaking in the uncured mold (in areas characteristic of the additive technique – on the joints of elementary thermoplastic layers), and consequently allows for later demoulding – removal of the base FFF model without damaging the mold surface and production of correct wax castings.
9. Damage (destruction, leakage) to valve models manufactured using the FFF additive technology from thermoplastics occurred in the areas where individual layers of the material extruded by the extruder were connected, both for models manufactured in horizontal and vertical orientation relative to the working platform (before and after the impregnation process).
10. Wax casting models of valve body parts were produced according to the developed assumptions of the hybrid manufacturing technique – using the additive manufacturing technology FFF and vacuum forming in silicone molds. The models will be used in the next stage of research aimed at the selection and analysis of selected light alloys.

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