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Kateryna Maiorova,
Olga Shypul,
Ihor Lysochenko,
Taras Hoptar,
Liudmyla Kapitanova,
Iryna Voronko

DESIGN OPTIMIZATION OF A MOLD FOR PRODUCING A COMPLEX-GEOMETRY BLADE

The object of research is a mold with complex geometry for casting a turbine blade prototype, made by 3D printing from Anycubic photopolymer resin and PETG (Polyethylene Terephthalate Glycol) polymer.

Problem to be solved: ensuring the necessary strength and rigidity of the mold during the assembly of half-molds by bolted connection with preliminary axial tension.

Using Siemens NX Advanced Simulation, finite element models of the mold were created and calculated. It was found that with significant preliminary axial tension, the limit stresses in the bolt hole area are exceeded, which limits the use of photopolymer resin. Reducing the tightening force improves the performance, but leaves a minimum margin of safety. The rigidity of the mold can be increased by using support pads, but such a design causes stress concentration in the bolted connections. The optimal calculation result was achieved when using PETG material: the safety margin increased to $\eta = 1.5$*, and the displacements did not exceed 0.04 mm. The PETG polymer, unlike photopolymer resin, is more elastic and plastic in the hardened state with higher strength. This allows to distribute the load over the material. The results obtained can be used for the manufacture of molds for casting and tooling in general, especially for a small batch of parts. The practical application of the technology under consideration is possible provided that the input parameters are correctly combined: material, bolt pre-tightening force and the use of support pads. PETG is recommended for molds operating under increased loads.*

Keywords: *stress-strain state, prototype, polymer molds, bolt pre-tightening simulation, additive manufacturing of tooling.*

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1. Introduction

Today, the development of additive technologies (AT) makes it possible to make new technological solutions, reducing the importance of traditional methods of manufacturing parts. Of particular interest are parts with complex geometry, since several traditional methods must be combined to manufacture such forms. In this case, turbine blades are considered, which under normal circumstances require the use of casting and subsequent finishing machining to give the part the required shape, which takes a lot of time and resources.

3D printing technology can be used to manufacture molds. The prospect of obtaining a tool that will have the necessary geometry and parameters, with minimal cost and wide possibilities during the production process, inspires the widespread use of this technology. But an important task arises – ensuring the necessary strength and rigidity in the forms manufactured in this way, especially during assembly and pre-tightening of bolted joints.

Many modern researchers have focused their attention on the possibilities of using AT for the manufacture of tooling. Most often, 3D printing appears in cases where it comes to complex geometry of parts. In the context of global trends to reduce costs and increase energy efficiency, additive technologies are becoming a key tool for the production of high-precision parts. For example, in Europe and the USA, polymer molds are already widely used for the manufacture of components of wind turbines and aircraft engines.

Research on the use of 3D printing to reduce the time of mold manufacturing and reduce costs at the preparation stages is described in the works [1, 2]. The authors emphasize that to achieve the required quality in castings, the correct design of the mold and the selection of the appropriate material are crucial. Despite the promising nature of additive technologies [1, 2], there are no recommendations on the optimal parameters (tightening force, material, geometry) for specific industries (e. g., aviation, energy). This limits the widespread introduction of polymer molds in industry.

The paper [3] considers the possibilities of replacing traditional metal molds for casting with polymer ones (photopolymer resins and thermoplastics). The use of polymer molds is especially relevant for small-scale production, where traditional methods are economically impractical. For example, in prototyping turbine blades or medical implants.

Some papers propose combining additive technology (3D printing) with traditional technology (injection molding) to improve tooling parameters during manufacturing [4], because such a combination can overcome the limitations of each individual technology: injection molding is characterized by high productivity for large-scale production, but has limited geometric freedom; 3D printing provides high flexibility, but is inferior in volume and speed.

Although the works [3, 4] consider replacing metal molds with polymer ones, it has not been systematically investigated how the physical and mechanical properties of PETG and photopolymer resins affect the durability of molds under cyclic loads. In particular, there is no data on the behavior of these materials during prolonged use under elevated temperatures or mechanical stress.

It is not enough to simply choose the mold material and print the mold. An important component of the design is the selection of the method of connecting the half-molds to each other. Bolted joints are most often used. To avoid unwanted deformations, opening of joints or premature loss of strength and stiffness, pre-tightening of the bolts is performed [5]. Bolt tightening is not a secondary, but a fundamental parameter that is often insufficiently taken into account in studies of polymer molds.

The authors of the publication [6] focus on different models for calculating bolted joints. They describe the differences in the pre-tension force when using different simulation methods and their impact on the analysis of the reliability of bolted joints. The work emphasizes that FEM (Finite Element Method) analysis is an effective tool in the analysis of the pre-tightening force of bolts.

Studies [5, 6] focus on the analysis of bolted joints, but do not take into account the influence of support pads on the stress distribution in polymer molds. This is critically important, as these areas often become stress concentrators, leading to premature failure.

Some studies [7] have proposed simplified FEM approaches for estimating and comparing general connection parameters (stiffness, load distribution). This can be useful if the mold model has a complex geometry, and excessive detail overloads the software and significantly slows down calculations. However, such methods should be used with caution in the context of studying polymer semi-forms, so that excessive simplification does not reduce the reliability of the results.

Creating bolt holes in composites can reduce the quality of the surface and the product as a whole. Thus, in [8], the influence of the method of processing the surfaces of the hole walls on the quality characteristics of the samples was investigated, so this issue is not considered in the work.

Despite numerous studies in the field of 3D printing, the problem of ensuring the strength and stiffness of polymer molds during operation remains unresolved. In particular, there are no systematic studies of the influence of design parameters (supporting platforms, bolt tightening force) on the stress-strain state of molds.

The aim of research was to find the optimal variant of the design of a mold with complex geometry, which can be manufactured using additive technologies (3D printing).

To achieve this aim, a number of tasks were set:

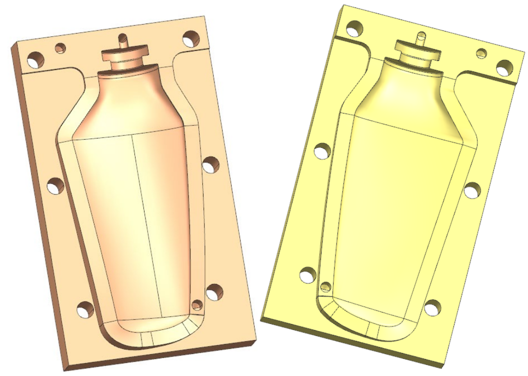
– develop a finite element model and calculate the stress-strain state;
– analyze the mold and determine the suitability of its material for use;
– investigate ways to improve the strength of the molds;
– compare Anycubic and PETG polymers;
– determine the possibilities of practical application of the mold.

Optimization of the design of molds using finite element simulation allows not only to increase their reliability, but also to develop recommendations for the industrial application of additive technologies.

2. Materials and Methods

The object of research is a mold of complex geometry for casting of a turbine blade prototype (Fig. 1), made by 3D printing from Anycubic photopolymer resin and PETG polymer (Polyethylene Terephthalate Glycol). This object was chosen because of its practical importance for the aviation and energy industries, where the requirements for accuracy and strength of parts are extremely high. Optimization of the mold design will increase its strength and rigidity, as well as reduce tooling costs compared to traditional metal molds.

The subject of research is the stress-strain state (SSS) and strength characteristics of the mold for different material options and bolt pre-tightening forces, as well as optimization of design parameters to ensure the required strength and rigidity of the mold.



a *b*

Fig. 1. Components of the mold: *a* – half-mold 1; *b* – half-mold 2

To obtain a finished product using casting technology with minimal deviation from the design documentation, it is necessary to meet a number of requirements. One of these requirements is to preserve the geometric parameters of the mold when pouring it with a solution of the finished product material [9].

The mold consists of two semi-molds of complex geometry (Fig. 1). The physical and mechanical characteristics of the Anycubic photopolymer resin are given in Table 1. The product for casting is a turbine blade prototype (Fig. 2).

Table 1

Physical and mechanical characteristics of Anycubic photopolymer resin

Parameter	Value	Parameter	Value
Density	1.13 g/cm^3	Tearing strength	40–50 MPa
Hardness	84–86 HS	Elongation at break	12–16%
Forming shrinkage	4.5–5.5%	Bending strength	50–60 MPa
Poisson's ratio adopted	0.25	Modulus of elasticity	1400–1600 MPa

Fig. 2. Turbine blade prototype

The mold is connected using a bolted connection (M8) with preload. The strength of the bolts is much higher than the strength of the mold material, which is why the strength of the half-molds is not the strength of the bolt, but the strength of the half-mold material. To determine the maximum possible bolt tightening force, a SSS calculation of this assembly was performed. Using the Siemens NX Advanced Simulation software (MSC Software, USA, Texas), a finite element model (FEM) calculation for strength was performed. The finite element method (FEM) was chosen because of its ability to accurately model complex geometries and analyze the stress-strain state of structures. This method allows taking into account the heterogeneity of materials, nonlinear effects and local stress concentrations, which is critically important for polymer molds manufactured by 3D printing. Siemens NX Advanced Simulation software was chosen due to its high level of accuracy and the ability to integrate with CAD systems for design optimization.

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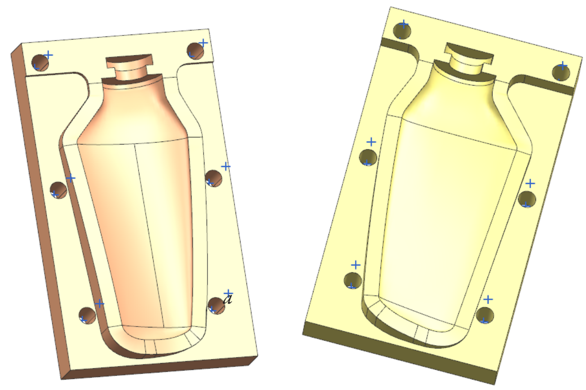
3. Results and Discussion

3.1. Results

Creating a finite element model involves simplifying the design solution. Simplification is performed in order to ensure that the finite element mesh is of better quality, since the veracity of the results obtained depends on this. Digital testing of the geometry of aircraft parts has been repeatedly used by this group of researchers [10], which is the basis for further accurate FEM simulation.

Before creating the FEM, a design analysis was performed to simplify it, taking into account design and technological features. Various functional holes, small radiuses of rounding's, etc. were removed. In addition, the deformed material is considered ideal with averaged mechanical properties [11].

When simplifying the model, it should be taken into account that although the decomposition of the technical system reduces the explicit complexity of the calculations, it also increases the so-called implicit complexity associated with the difficulties of determining the expected properties of the system from the characteristics of its elements, significantly complicating the procedures for confirming individual design solutions obtained within the framework of this process [12]. The simplified design model of the chill is presented in Fig. 3.



a *b*

Fig. 3. Simplified models of the mold: *a* – half-form 1; *b* – half-form 2

After simplifying the model, a finite element mesh was created. For this purpose, the size of the edge of the finite element was selected. A finite element of the CTETRA type (4) with a size of 1 mm with the material of this photopolymer resin was used. Thus, two half-forms of the mold were modeled. Simulation of bolted connections provided for the formation of rigid multi-point limiting elements (1D-elements) with RBE2 properties in each hole of the half-forms. The connection of these elements to each other was performed using 1D-elements of the CBA beam type with the physical properties of CROD. When creating the CROD element, the bolt material (steel) and the geometric characteristics of the cross-section of the element were specified. The created FEM of the mold half-form is shown in Fig. 4.

During the creation of the calculation model, contact type simulation objects were created in the areas where the mold halves adjoin each other, with the parameters of contact interaction without penetration of the mold halves into each other.

The load was set to a preliminary tightening of the bolts by the value $P = 12$ kN. The ends of the mold halves were chosen as the fastening, which were prohibited from any movements. The calculation model is presented in Fig. 5.

The calculation results are presented in Fig. 6–8.

The results of the calculated movements show that the mold structure is quite rigid, the maximum movements reach 0.45 mm over the contact area of the mold halves. This allows to conclude that the opening of the joint in the half-forms will be minimal and permissible.

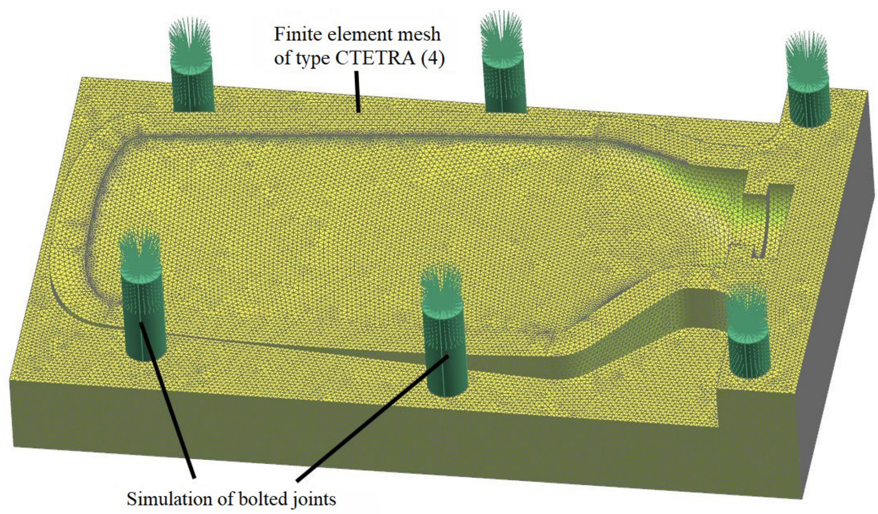


Fig. 4. Mold half-form FRM

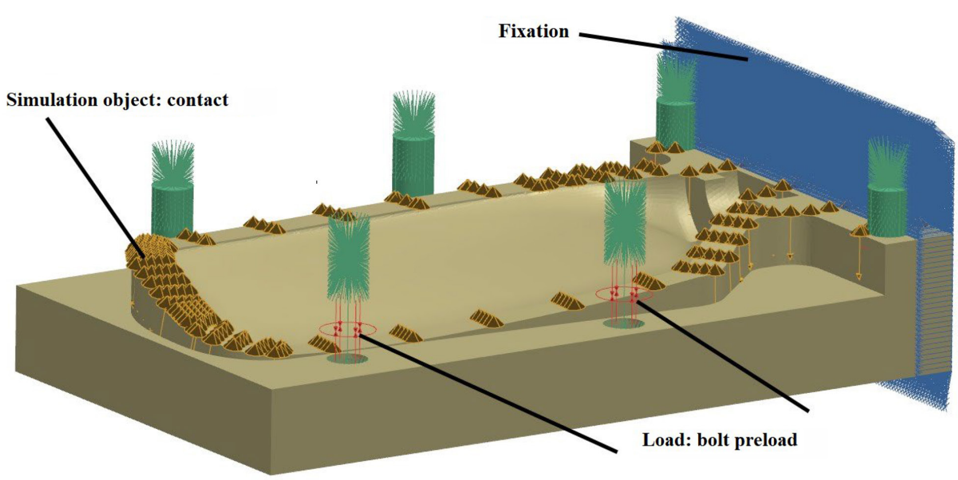


Fig. 5. Calculation model of the mold half-form

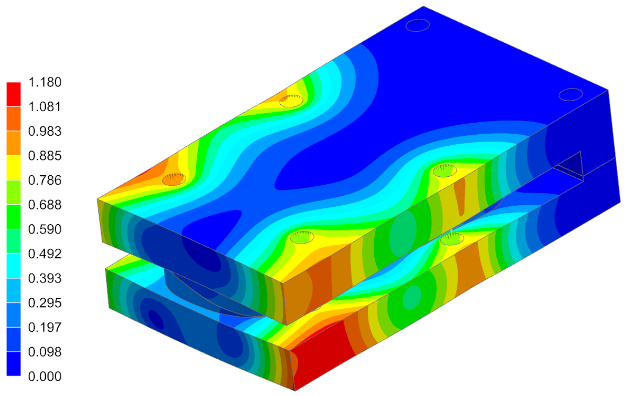


Fig. 6. General view of the mold structure movements

At σ^E = 120 MPa and σ_B = 40 MPa, the quantitative value of the overload is equal to 3.

Based on this, it is concluded that the pre-tightening force of the bolts must be reduced by at least 3 times, or sleeves must be used in the connection.

The pre-tightening force of the bolts was reduced by 3.5 times. The results of the calculation with the applied force P = 3.4 kN are presented in Fig. 9, 10.

The maximum equivalent stresses are σ^E = 36 MPa. The safety factor η, which characterizes the reliability degree of the structural connection, is determined by the formula

$$\eta = \frac{\sigma_B}{\sigma^E}. \qquad (2)$$

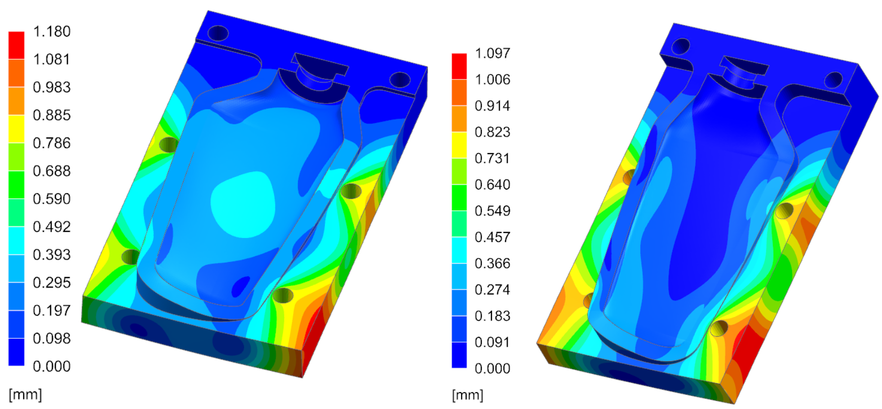
Therefore, in the case of using pre-tightening of bolts P = 3400 N when assembling the mold, the safety factor will be equal to η = 1.12. As recommendations, it is possible to suggest the use of steel bushings between the half-molds and increasing the contact area of the bolt and nut with the mold surface using wide washers.

Increased contact area of half-molds. The calculation model is shown in Fig. 11. The new model with support pads for the contact of the half-molds is pre-tightened with bolts. It is assumed that each bolt is tightened to P = 12 kN.

The calculation results are given below. Fig. 12 shows the SSS in the half-molds after preliminary tightening of the joints.

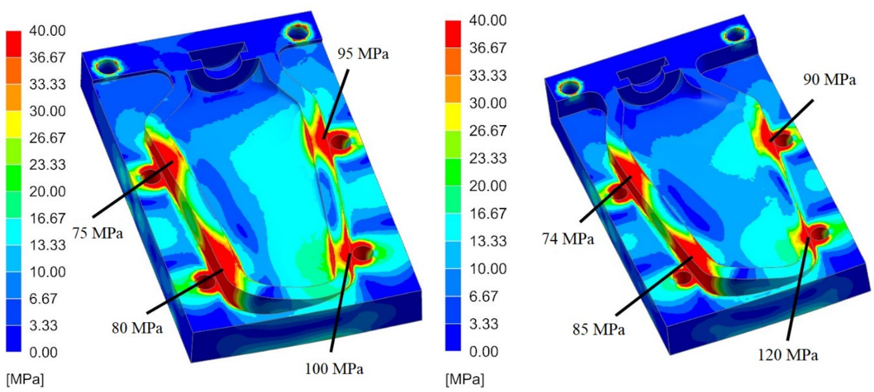
Fig. 13 shows the SSS of each of the half-molds.

The results of the calculated displacements show that due to the added support pads, the mold received additional rigidity, the maximum displacements reach 0.03 mm. These displacements are due to a rather high tightening force. This allows to conclude that when tightening the bolts there is a risk that the mold may break precisely during the tightening of the bolts – the influence of latent deformation energy on the operational properties of the parts is significant, which is especially important for precision products [13].



a *b*

Fig. 7. Movement pattern of the mold halves: *a* – half-form 1; *b* – half-form 2



a *b*

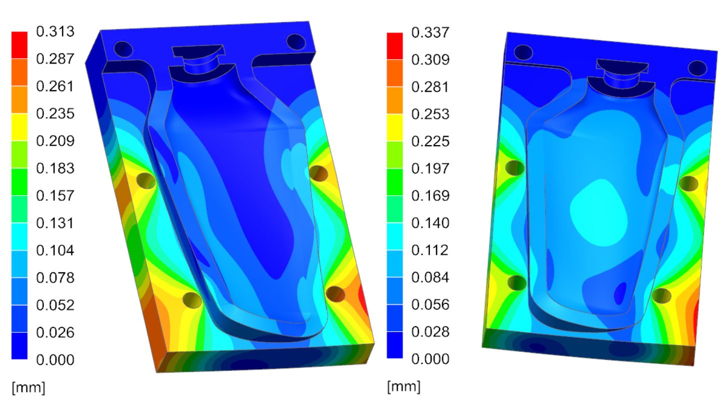
Fig. 8. Stressed state of the half-forms according to the von Mises criterion: *a* – half-form 1; *b* – half-form 2

For all calculations, the equivalent stresses were determined according to the criterion of the maximum specific potential energy of "Mises criterion" deformation. The results of the stress calculation show that the structure is not strong in the area of the bolt holes for this problem statement. The maximum equivalent stresses are equal to σ^E = 120 MPa.

To determine the quantitative value of the overload Δ, the equivalent stresses σ^E were compared with the ultimate strength limit σ_B according to the formula

$$\Delta = \frac{\sigma^E}{\sigma_B}, \qquad (1)$$

where σ^E – the equivalent stresses according to Mises, calculated in the process of FEM stress analysis; σ_B – the ultimate strength limit at rupture, obtained experimentally.



a *b*

Fig. 9. Pattern of half-mold movement: *a* – half-mold 1; *b* – half-mold 2

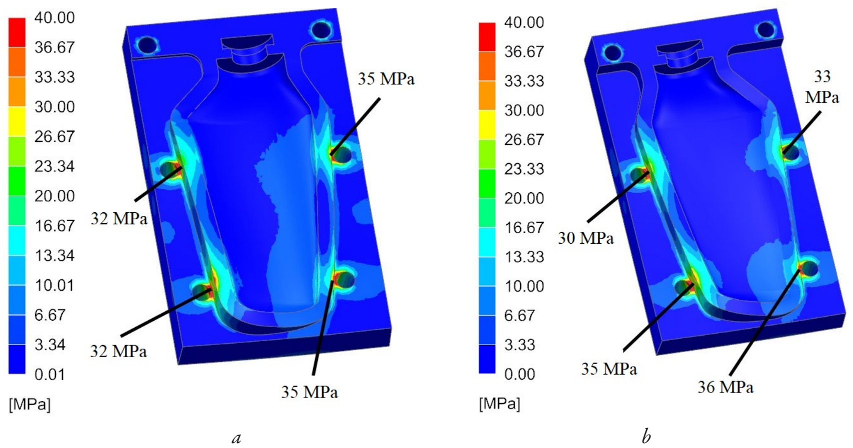


Fig. 10. Stressed state of half-molds according to the von Mises criterion: *a* – half-mold 1; *b* – half-mold 2

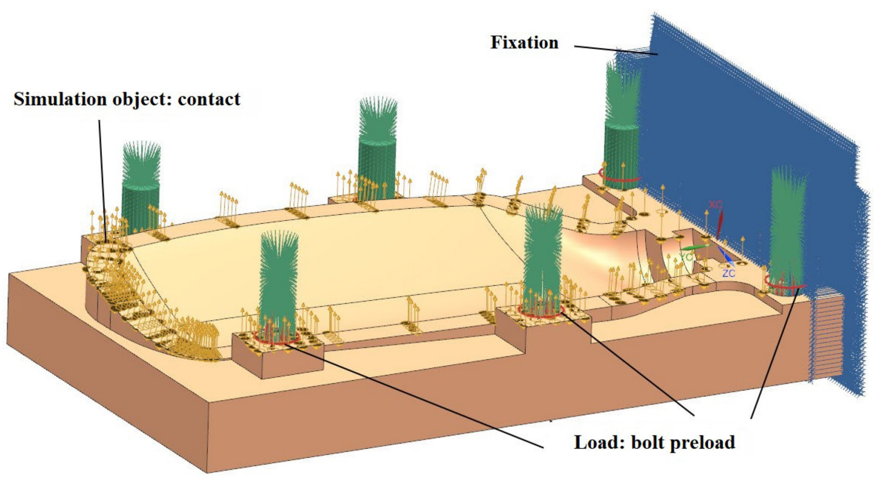


Fig. 11. Calculation model of the half-mold

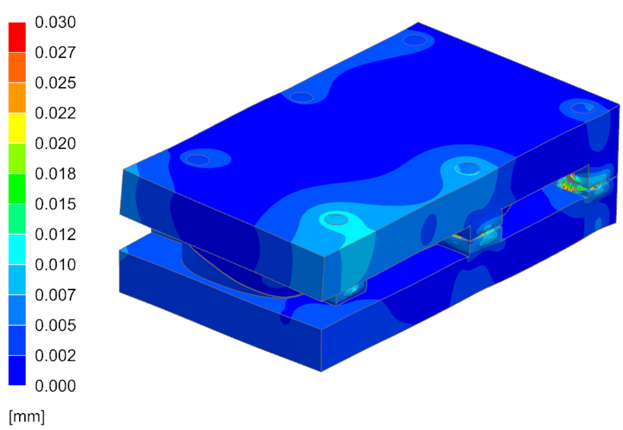


Fig. 12. General pattern of the displacements of the mold structure

The stress concentration (Fig. 14) is observed precisely in the contact zone of the support surfaces of the half-molds. The maximum equivalent stresses on average are: σ^E = 90 MPa.

The safety factor was determined by formula (2).

In the case of using support pads and pre-tightening of bolts P = 12 kN when assembling the mold, the safety factor η = 0.44. Therefore, the strength of the mold is not ensured, it is necessary to choose a stronger material, or reduce the force of pre-tightening. The degree of reduction was determined by formula (1). The result 2.3 was obtained.

It was decided to develop a model of a mold made of PETG plastic and assembled with a bolt tightening P = 12 kN.

The mechanical characteristics of the material are presented in Table 2.

Fig. 15 shows the SSS in PETG plastic half-molds after pre-tightening the joints.

Fig. 16 shows the SSS of each of the half-molds.

The results of the calculated displacements show that due to the added support pads, the mold received additional rigidity, the maximum displacements on average reach 0.02–0.04 mm.

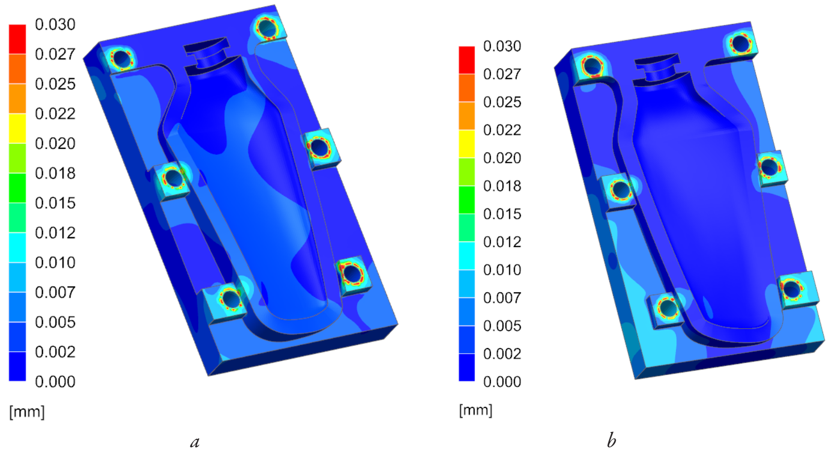


Fig. 13. Displacement patterns of the half-molds: *a* – half-mold 1; *b* – half-mold 2

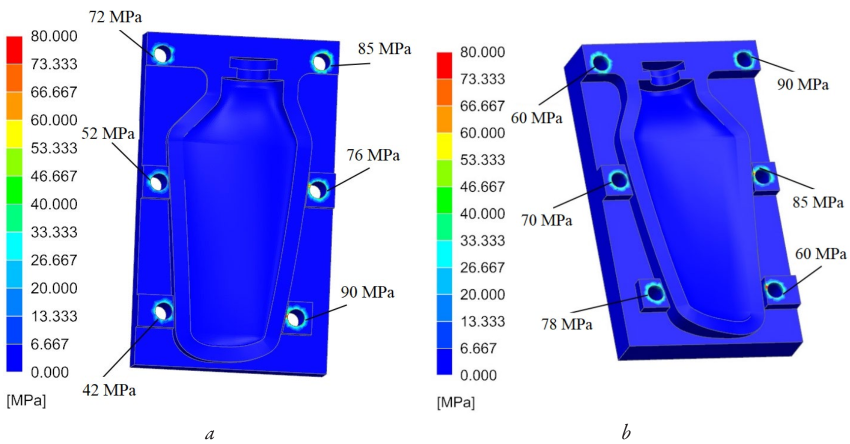


Fig. 14. Stressed state of half-molds according to the von Mises criterion: *a* – half-mold 1; *b* – half-mold 2

Table 2

Physical and mechanical characteristics of photopolymer resin

Direction	Modulus of elasticity, E, GPa	Poisson's ratio, μ	Tensile strength, σ_B, MPa
X	2.2	0.38	60
Y	2.0	0.37	50
Z	1.6	0.35	40

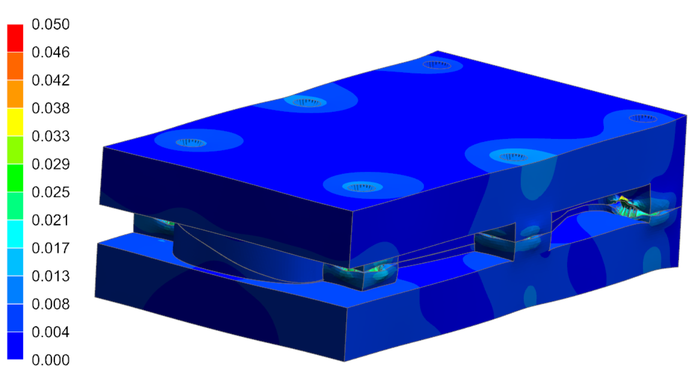


Fig. 15. General pattern of the displacements of the mold structure

The concentration of stresses (Fig. 17) is observed precisely in the contact zone of the support pads of the half-molds. The maximum equivalent stresses on average are equal to $\sigma^E = 40$ MPa. Using formula (2), the safety factor was determined, taking the strength of the filament along the X axis as the ultimate strength. In the case of manufacturing a mold from PETG material, using support pads and pre-tightening the bolts $P = 12$ kN when assembling the mold, the strength of the mold is ensured, $\eta = 1.5$.

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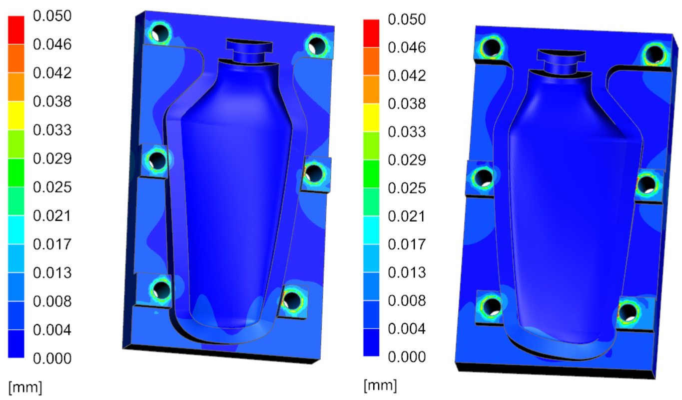

Fig. 16. The displacement patterns of the half-molds: *a* – half-mold 1; *b* – half-mold 2

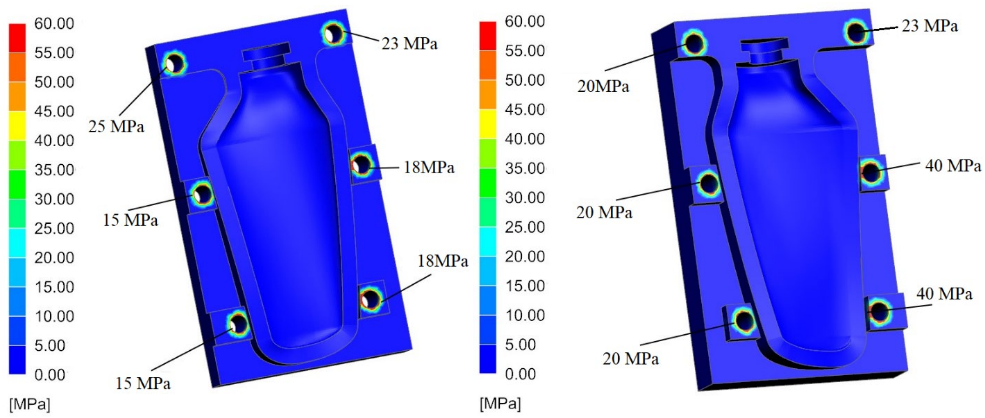

Fig. 17. The stressed state of the half-molds according to the von Mises criterion: *a* – half-mold 1; *b* – half-form 2

3.2. Discussion

Practical significance. The research proves the possibility of using additive technologies for the manufacture of molds and technological equipment in general, especially if the goal is to manufacture parts of complex geometry in small quantities. PETG has proven itself as a material that combines high strength, rigidity and plasticity, and its use is especially beneficial in conditions of short production times and limited resources. Obtaining optimal parameters for pre-tightening the bolts allows to save the mold from destruction at the stage of assembling the half-molds and during the casting of the part. And this, in turn, ensures accurate transmission of the dimensions of the part being cast.

Research limitations. First, the study was performed as a simulation in the Siemens NX Advanced Simulation software, the models were built in idealized conditions using simplifications. In reality, the structure of the materials is heterogeneous, there are temperature fluctuations and unevenness during loading. Secondly, examples of application on only two types of polymers were considered, while polymers and composite materials are gaining increasing popularity in various fields, and it would be advisable to further consider the manufacture of technological equipment from other materials with similar properties.

The influence of martial law conditions. The study was conducted during martial law in Ukraine. Conditions for the development of scientific activity often leave much to be desired. For example, full-scale tests were limited due to the unavailability of some materials, and the use of software for calculations has certain limitations due to the high cost of some tools within the program. But, despite the difficulties, the authors were able to prove the relevance of using additive technologies to create samples of complex shape and equipment for their manufacture without the use of traditional expensive metal molds. This once again proves the relevance of the use of AT in such industries as mechanical and aircraft engineering.

Prospects for further research. Based on the obtained result, the following areas of research can be considered in the future:

- conduct experimental verification of the obtained FEM analysis results taking into account real conditions (temperature changes and their impact on the smoothness of the casting process, etc.);
- investigate the possibility of multiple uses of molds made of polymer materials;
- investigate similar materials, the strength characteristics of which are not lower than those considered in the article (for example, polymer composites reinforced with special fibers);
- investigate the possibility of improving the strength of stress concentrator zones by combining 3D printing with the addition of metal inserts;
- find the optimal combination of geometry and material using modern CAD/CAE systems.

4. Conclusions

1. The work developed a finite element model of a mold with complex geometry for casting turbine blades using two polymer materials: photopolymer resin Anycubic and PETG. It was found that the most influential factors in the reliability of the structure are the selected material and the pre-tightening force of the bolts.

2. It was found that a mold made of photopolymer resin cannot withstand a tightening force of 12 kN, since stresses under such conditions arise that are three times higher than the strength limit of the material. The destruction of the mold can only be stopped by reducing

the tightening force by 3.5 times, but under such conditions the practical application of such forms is very limited.

3. An attempt to strengthen the zones of the photopolymer mold that receive the greatest load by means of support pads gave a negative result. Stress concentrators that arise near the pads reduce the safety margin to a dangerous level. This once again proves that this material should not be used for high bolt tightening.

4. When using PETG material, good results were obtained: tightening force $P = 12$ kN, high safety margin ($\eta = 1.5$), movement in the material not more than 0.04 mm. Therefore, PETG can be used under conditions of significant loads.

5. Practical application is the possibility of using PETG material for the manufacture of molds of complex shape. At the same time, they will have high strength and durability, so they can be successfully used for the manufacture of parts of complex geometry in small-scale or single-unit production. Also, local stress concentrations in the areas of bolted joints can be reduced by using reinforcing elements (sleeves and washers).

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The research was performed without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Kateryna Maiorova: Conceptualization, Resources, Project administration; ***Olga Shypul***: Methodology, Supervision; ***Ihor Lysochenko***: Investigation, Resources; ***Taras Hoptar***: Methodology, Writing – original draft; ***Liudmyla Kapitanova***: Conceptualization, Validation; ***Iryna Voronko***: Conceptualization, Writing – review and editing.

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Kateryna Maiorova, *PhD, Associate Professor, Head of Department of Aircraft Manufacturing Technologies, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0003-3949-0791*

Olga Shypul, *Doctor of Technical Sciences, Professor, Department of Aircraft Manufacturing Technologies, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0002-1356-5831*

Ihor Lysochenko, *CNC Machine Operator, Joint-Stock Company "FED", Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0002-4407-0305*

Taras Hoptar, *Stress Engineer of Fuselage Strength Calculation Design Department, Joint-Stock Company Antonov, Kyiv, Ukraine, ORCID: https://orcid.org/0009-0005-9405-6279*

Liudmyla Kapitanova, *Doctor of Technical Sciences, Associate Professor, Professor of Department of Aircraft and Helicopter Design, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0003-3878-6734*

✉***Iryna Voronko,*** *PhD, Associate Professor, Department of Aircraft Manufacturing Technologies, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine, e-mail: i.voronko@khai.edu, ORCID: https://orcid.org/0000-0002-9689-6977*

✉*Corresponding author*