UDC 621.742
DOI: 10.15587/2706-5448.2026.357430

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DEVELOPMENT OF A HYBRID TECHNOLOGICAL SCHEME FOR MANUFACTURING PATTERN EQUIPMENT FOR PUMP IMPELLERS

The research deals with the technological process of manufacturing pattern equipment for pump impellers with curved blades. Pattern equipment is a key element of foundry production, since it determines the geometry and quality of the future casting.

The paper addresses the problem of ensuring the dimensional accuracy and quality of pattern equipment for pump impellers. It is shown that three-axis CNC machining is limited in the manufacture of curved blades, whereas the use of five-axis machining centers involves significant costs and higher qualification requirements. Under these conditions, a transition to hybrid technological schemes becomes justified, combining three-axis CNC milling with additive 3D printing.

The research aimed to develop and substantiate a hybrid technological scheme for manufacturing pattern equipment. The scheme is based on a rational division of operations: base surfaces are produced by CNC milling, while complex-geometry elements, namely negative blade sections, are manufactured using 3D printing and digital inspection. The research employs CAD/CAM design, three-axis CNC machining, additive manufacturing, and measurement-based control methods. A comparative analysis of conventional and hybrid approaches was carried out. The hybrid technology ensures geometric deviations of the base surfaces within 0.1–0.3 mm, while additively manufactured blade elements achieve deviations within 0.1–0.15 mm. Due to the combination of CNC milling and 3D printing, the technological route is reduced by 30–40%, and the cost of pattern equipment decreases by 20–30% compared with five-axis machining.

The proposed scheme can be implemented at industrial enterprises equipped with three-axis CNC machines and additive manufacturing systems, without expensive five-axis machining centers.

Keywords: *model equipment, working wheels, CNC milling, additive technologies, digital control.*

Received: 04.02.2026
Received in revised form: 29.03.2026
Accepted: 13.04.2026
Published: 30.04.2026

How to cite
Shelepko, P., Ponomarenko, O. (2026). Development of a hybrid technological scheme for manufacturing pattern equipment for pump impellers. Technology Audit and Production Reserves, 2 (1 (88)), 32–37. https://doi.org/10.15587/2706-5448.2026.357430

1. Introduction

In mechanical engineering today, the manufacture of model equipment for pump impellers occupies a very important place, since the geometry of cast blanks affects the reliability, energy characteristics and operational life of pumping equipment. From a foundry point of view, closed impellers most often belong to the fourth (IV) or fifth (V) class of casting complexity according to DSTU 26645–85. This is due to the need for strict adherence to geometric parameters, precise adjustment of internal channels, increased requirements for weight and dimensions and minimum tolerances. Deviations in the profile of blades and mating surfaces increase hydraulic losses and reduce the efficiency of pumps. That is why increased requirements are placed on the accuracy and stability of the geometry of model equipment, especially in the production of impellers with a complex configuration of blades [1, 2].

The production of model equipment by yesterday's methods, based on manual operations using templates and universal equipment, showed higher labor intensity and were limited by the ability to ensure the necessary geometric accuracy. These limitations were especially evident for the formation of curved surfaces of blades, where the main share of accuracy depended on the qualifications of the performer and the amount of manual finishing, which reduced the accuracy of obtaining the required shape and increased the production time [3].

The breakthrough in model production in the last twenty years was based on the transition from manual design methods to digital technologies. Such as CAD/CAM design, machining on numerically controlled machines and the use of digital geometry control tools. At the same time, the complexity of the impeller design and the increase in requirements for the quality of cast workpieces necessitate increasing the accuracy of model equipment and the stability of the technological processes for its manufacture.

If to analyze scientific publications and production experience, it is possible to see that three-axis CNC machining is the most widely used and economically optimal method of forming the base, detachable and landing surfaces of the tool. But in this case, when processing complex curved blade surfaces, this approach also has some technological limitations, primarily related to the availability of the tool, the number of resets and a decrease in the accuracy of forming the geometry. The use of five-axis machining centers allows to partially eliminate these limitations, but is accompanied by significant capital costs. In addition, increased requirements for the level of personnel qualification, which limits the possibility of their application in serial and small-scale production [4]. Additive technologies have been developing very rapidly in recent years and demonstrate high efficiency in the manufacture of elements of complex geometry. At the same time, the issues of ensuring dimensional accuracy, geometry reproducibility and the introduction of 3D printing processes into the general technological route of model equipment production remain insufficiently systematized and require additional analysis, taking into account the specifics of this production. The above circumstances reveal a technological contradiction between the requirements for high accuracy of model equipment for pump impellers and the limited capabilities of traditional methods of its manufacture. This necessitates the research and analysis of combined technological solutions based on the optimal combination of mechanical processing and additive technologies with the use of digital geometry control methods [5].

The object of research is the technological process of manufacturing model equipment for pump impellers that have curved blades.

The aim of research is to develop a hybrid technological scheme for manufacturing model equipment for pump impellers.

Research objectives:

1. To propose a conceptual solution for a hybrid technological scheme.
2. To build a 3D model of the impeller based on the original design documentation.
3. To implement the technology for manufacturing basic elements of model equipment on three-axis CNC milling machines using plate materials.

2. Materials and Methods

The research used a drawing of the pump impeller part. Based on it, a 3D model of the casting was built in the SolidWorks CAD system, after which a 3D model of the impeller model tooling was developed. Control programs for machining were prepared in the PowerMill CAM system (Autodesk, USA) using strategies used for three-axis milling.

To manufacture the basic elements of the model tooling, plate materials traditionally used in model production were used, in particular plywood and MDF. The blanks were pre-glued, and then subjected to mechanical processing. The basic elements of the model tooling, in particular the models of the top and bottom of the mold, as well as the bases of the core boxes, were manufactured using the three-axis CNC machining method on a SUDA milling machine (China). Mechanical processing was performed in two stages. At the roughing stage, the basic geometry of the blanks with an allowance was formed using end monolithic milling cutters. At the finishing stage, the allowance was removed and the final shaping of the surfaces was performed using spherical carbide cutters in accordance with the 3D model and the requirements for the assembly of the tooling. 3D sampling and contour sampling strategies were used for roughing, and for finishing, machining strategies with constant Z and vertical plus sloping trajectories were used [6, 7].

The technological route was formed taking into account the functional purpose of the elements of the model tooling, the geometric complexity of the surfaces, the requirements for basing and assembly accuracy. The base, landing and detachable surfaces were intended for manufacture by the method of three-axis CNC milling, while the elements of complex curvilinear shape were intended for the method of additive manufacturing. This approach was used to distribute operations between mechanical and additive processing in accordance with the technological capabilities of each method [8].

The complex-profile elements of the model tooling, in particular, curved blades and individual inserts, were manufactured by FDM printing on a Creality Ender-3 3D printer (Creality, China) using PETG plastic. During additive molding, the orientation of the part during printing, the layer height and the configuration of the supports were taken into account. After printing, the supports were removed and minimal mechanical finishing of the elements was performed in the places of their subsequent connection with the base parts of the tooling [9].

Experimental work was carried out in production conditions. Preparation and gluing of blanks, mechanical processing of basic elements on CNC machines and subsequent finishing were performed in the production units used for the manufacture of model tooling. Finishing, fitting and assembly of elements were performed in the model shop. Additive manufacturing of curved blades and inserts was carried out in a separate working area intended for 3D printing. After the manufacture of milled and printed elements, their staged control was carried out before final assembly.

To validate the proposed technological scheme, 3D scanning of manufactured elements was used using an Artec Eva scanner (Artec 3D, Luxembourg). The obtained data were compared with the original CAD model with orientation according to the base surfaces. Control was performed for the base, landing and functionally significant surfaces, as well as for the connection zones of individual elements of the model tooling. Additional technological validation was carried out at the assembly stage by checking the mutual fit of the elements, the possibility of installing additively manufactured parts into the base parts of the tooling and the consistency of the surfaces in the model kit.

3. Results and Discussion

3.1. Conceptual solution for a hybrid technological scheme

The paper proposes a hybrid technological scheme for manufacturing model equipment for pump impellers. The scheme distributes operations between three-axis CNC machining and additive manufacturing, depending on the functional purpose and geometric complexity of the elements. In this paper, a hybrid technological scheme means a combination of two methods of forming within one technological route: mechanical machining for base surfaces and FDM printing for complex-profile elements, primarily curved blades.

The proposed scheme assumes that the basic elements of the model equipment are manufactured from plate materials on three-axis CNC milling machines, while elements of complex spatial shape, inaccessible or poorly accessible for effective three-axis machining, are formed by an additive method. This approach allows to avoid multiple resets of the workpiece, to reduce the volume of manual finishing and to maintain the accuracy of assembly due to the mechanical manufacturing of functionally significant surfaces.

The structure of the proposed hybrid technological scheme is shown in Fig. 1. Within its framework, digital design, mechanical processing, additive manufacturing and geometry control are considered as interconnected stages of a single technological route. It is this distribution of operations that was laid down as the basis for the further design of the 3D model of the impeller, model tooling and implementation of the manufacturing process of basic elements.

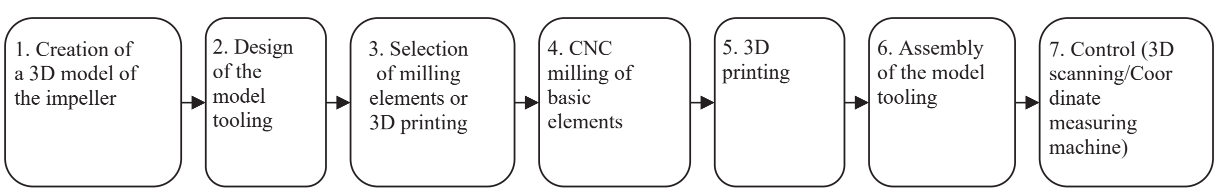


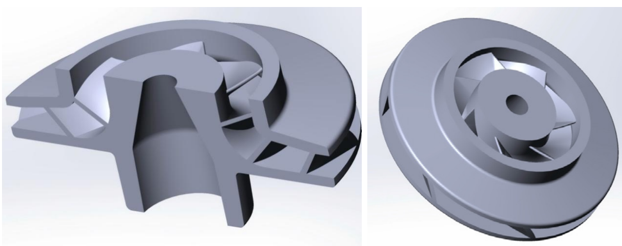
Fig. 1. Structure of the technological scheme for manufacturing a model tooling of a pump impeller

ISSN-L 2664-9969; E-ISSN 2706-5448

3.2. 3D model of the impeller

The impeller is the main element of the pumping equipment, which directly provides the transfer of energy of the fluid flow. The geometry of the impeller significantly affects the hydraulic characteristics, efficiency and reliability of the pump. For foundry production, this part is complex due to curved blades, internal channels and conjugate surfaces. This imposes increased requirements on the accuracy of the model tooling and the quality of the future casting. Therefore, the impeller was chosen as an object for building a 3D model and further designing the model tooling.

Based on the original design documentation, a 3D model of the closed pump impeller was built in the SolidWorks (Dassault Systèmes) CAD system. The model reproduces the main geometric elements of the part, in particular the cover and drive discs, the hub and curved blades. The general view of the constructed 3D model is shown in (Fig. 2).



a *b*

Fig. 2. 3D model of a closed pump impeller:
a – sectional view; *b* – general view

The resulting 3D model was used as a basis for further design of the model tooling. On its basis, the construction of models of the top and bottom of the mold was performed, the connector planes and the configuration of the main elements of the model kit were determined. The design of the model tooling of the impeller is shown in (Fig. 3).

a *b*

Fig. 3. Design of the model impeller tooling: *a* – upper half; *b* – lower half

A 3D model of the core box with removable blades was designed separately. Its design involves division into a base part and separate blade elements, which made it possible to lay down different methods of manufacturing individual parts of the tooling even at the digital design stage. The 3D model of the core box is shown in (Fig. 4).

Thus, the constructed 3D model of the impeller and the derived models of the tooling elements became the basis for the implementation of a hybrid technological scheme for the manufacture of model tooling.

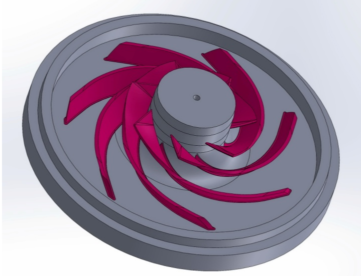


Fig. 4. Core box of the impeller with curved blades from 3D printing

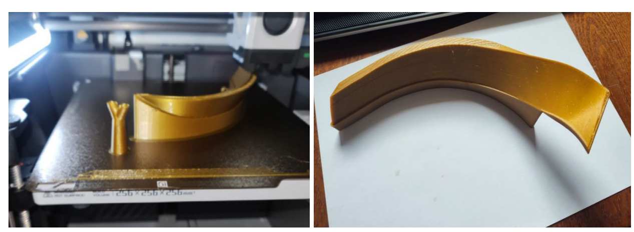
3.3. Implementation of the technology for manufacturing basic elements of model tooling on three-axis CNC milling machines

The manufacture of basic elements of model tooling was carried out on three-axis CNC milling machines using board materials: plywood and MDF. Such elements included models of the top and bottom of the mold, as well as the base parts of the core boxes. It is for these elements that the accuracy of basing, the correctness of the mutual arrangement of surfaces and the stability of assembly are decisive. Mechanical processing was carried out in two stages: roughing and finishing. At the roughing stage, the basic geometry of the workpieces with an allowance was formed, and at the finishing stage, the final shaping of the basic and functionally significant surfaces was performed in accordance with the CAD model (Fig. 5).

a *b*

Fig. 5. The milling of the elements of the model tooling on a three-axis CNC machine: *a* – finishing of the impeller core box; *b* – roughing of the model of the top and bottom of the impeller

The curved impeller blades were manufactured separately using the FDM printing method. This approach allows to recreate complex geometry that is inaccessible to three-axis CNC machining. An example of manufacturing a blade using the FDM printing method is given (Fig. 6).



a *b*

Fig. 6. Impeller blade manufactured by FDM printing:
a – 3D printing process (fragment of the printer's working area);
b – finished blade after printing

The final stage was the assembly and adjustment of the model tooling with blade adjustment, installation of structural elements, geometry verification, fastening of the sides and application of a protective coating. The general appearance of the finished model after completion of all technological operations is shown in Fig. 7.

Table 1 presents a comprehensive comparison of technological and economic indicators of manufacturing the pump impeller model tooling using different manufacturing approaches: manual technology, three-axis and five-axis CNC machining, additive manufacturing and hybrid technology. The comparison was made for the same geometrically complex model tooling, which ensures the correctness of the comparison of results. The analysis shows that five-axis CNC machining provides minimal manufacturing time and high accuracy of shaping, but is accompanied by significant capital and operating costs, which reduces its economic feasibility for model production. Additive technologies are characterized by high flexibility and low equipment requirements, but do not provide the necessary accuracy of the base and landing surfaces and require additional finishing, and also take a very long time to manufacture. Hybrid technology, based on a combination of three-axis CNC machining of base elements and additive shaping of complex-profile sections, demonstrates the optimal balance between accuracy, labor intensity and cost. Reducing the proportion of manual finishing, reducing the volume of machining and high flexibility in making changes to the design ensure the greatest economic efficiency of the hybrid approach while maintaining the required geometry of the model equipment.

Table 2 shows the achievable ranges of surface roughness and geometry accuracy during finishing of model tooling for pump impellers. Manual processing is characterized by a high dependence of the result on the worker's qualifications and limited reproducibility. Three- and five-axis CNC machining provide more stable indicators of surface quality and accuracy, while five-axis machining gives minimum Ra values due to optimal tool orientation. Additive technologies are characterized by increased surface roughness, but as part of a hybrid scheme they allow to provide the necessary accuracy of curved elements while reducing the labor intensity of manufacturing [10].

To check the accuracy of the manufactured elements, 3D scanning was used using the Artec Eva scanner. The obtained data were compared with the original CAD model. Scanning showed that the deviations in the mating zones of additively manufactured blades with milled base parts do not exceed 0.2 mm, which is consistent with the range of typical accuracy for hybrid technology (0.1–0.3 mm, Table 2). This allowed timely adjustment of the seats before final assembly.

a *b* *c*

Fig. 7. Elements of the impeller model tooling after manufacturing: *a* – model of the lower part of the impeller; *b* – model of the upper part of the impeller; *c* – lower part of the core box with additively manufactured blades

Table 1

Comparison of technological and economic indicators of manufacturing model equipment of the pump impeller

Indicator	Manual technology	3-axis CNC	5-axis CNC	Additive	Hybrid
Geometric complexity (method capabilities)	Limited	Limited	High	Very high	High
Shape accuracy	Medium	High for simple surfaces	High	Medium	Medium-high
Surface quality/roughness	Medium	Medium-high	High	Low-medium	Medium-high
Manufacturing time, hours	60–100	35–45	15–20	50–80	20–25
Manufacturing cost, standard units	1.0	0.7–0.8	1.3–1.5	0.6–0.7	0.65–0.75
Equipment cost/expense level	Low	Medium	Very high	Low-medium	Medium
Required personnel qualification	High (manual finishing)	Medium	High	Medium	Medium
Mechanical processing share, %	20–30	70–80	90–95	5–10	40–50
Manual finishing share, %	70–80	20–30	10–15	25–35	10–15
Flexibility of making changes to the design	Low	Medium	Low	Very high	High
Geometry reproducibility	Low	High	Very high	Medium	Medium-high
Economic efficiency (for model production)	Low	Medium	Low	Low	High

Note: the comparison is made for the same model tooling. The time and relative cost indicators are given as typical ranges. Other indicators are given in qualitative form (comparative assessment).

Table 2

Comparison of surface roughness and accuracy of model tooling with different processing technologies

Machining technology	Equipment material	Ra, µm	Typical accuracy, mm
Manual machining (finishing)	Wood/plywood	6.3–12.5	0.5–1
3-axis CNC (finishing)	MDF/plywood (dry blanks)	3.2–6.3	0.15–0.35
5-axis CNC (finishing)	MDF/plywood (dry blanks)	1.6–3.2	0.10–0.15
3D printing FDM	PLA/PETG	6.3–12.5	0.1–0.25
Hybrid technology	MDF/plywood + 3D printing FDM	1.6–3.2	0.1–0.3

Note: typical values for finishing of model equipment elements of pump impellers are given. Materials: Wood, MDF, plywood (dry blanks) and polymeric materials for additive molding.

3.4. Discussion

The results shown in Fig. 5–7 and in Tables 1, 2 indicate that it is advisable to distribute the operations in the manufacture of model equipment taking into account the geometry of specific elements. As shown in Fig. 1, within the framework of the proposed hybrid technological scheme, the base, landing and detachable surfaces are manufactured by the method of three-axis CNC machining, while elements of complex curvilinear shape, in particular curved blades and individual inserts, are manufactured by the additive method of 3D printing. This approach distinguishes the proposed scheme from traditional manufacturing, in which the entire model tooling is mainly manufactured by one method. As can be seen from Fig. 5–7, three-axis CNC machining is most appropriate for the base and landing surfaces, as well as for the connector planes, since it is for these areas that the stability of the base, assembly accuracy and predictability of the geometry are decisive. At the same time, additive molding is more suitable for curved blades and individual inserts, since it allows to reproduce complex spatial geometry without special additional tooling and without multiple resets. Therefore, the advantages of each method are realized in that part of the technological route where they are most effective.

As can be seen from the data in Table 1, hybrid technology occupies an intermediate position between fully mechanical and fully additive schemes. It provides a balanced ratio of accuracy, labor intensity and cost. Five-axis CNC machining is characterized by high accuracy and speed, but requires expensive equipment and highly qualified personnel. Additive manufacturing is flexible, allows to form complex shapes, but the base and landing surfaces without further processing do not provide the required quality. Therefore, the hybrid approach reduces the need for five-axis machines and at the same time provides the necessary accuracy on complex elements.

From the data in Table 2 it is clear that the difference in roughness and accuracy between the methods is not a contradiction, but determines the rational limits of application of each method. In the hybrid scheme, machining ens ures the accuracy of the base surfaces, and 3D printing – the reproduction of complex geometry. Digital control is of great importance in this. As shown in subsection 3.3, 3D scanning allows to detect deviations in the places of connection of parts before assembly and correct them in a timely manner.

The limitations of research are that the hybrid scheme was tested only on one part – the impeller of a pump with curved blades. Therefore, the possibility of its application for other products depends on the geometry, accuracy requirements, stability of printing on an FDM printer, the quality of finishing of printed parts and assembly. It should also be taken into account that FDM printing provides lower accuracy and worse roughness than SLA or DLP. It is impossible to completely abandon the machining of the base and landing surfaces. The errors of 3D scanning depend on the material and conditions of the shooting, and the size of the parts is limited by the working area of the printer [11]. In addition, only a few types of impeller geometries were considered in the research. Therefore, the results for other blade profiles require additional verification.

In practice, the proposed approach can be used at enterprises engaged in the design and manufacture of model equipment. These results can also be useful for foundries, where pump impellers and other parts with complex curved surfaces are manufactured. The main advantage of such a hybrid technology is that it allows to reduce the dependence on five-axis machining centers. At the same time, the required accuracy of complex-profile elements is maintained. The combination of 3D printing and three-axis CNC machining makes it possible to reduce the duration of tooling manufacturing and reduce its cost. It is worth noting that better compliance of CAD geometry models and control of dimensional chains at the manufacturing stage have a positive effect on the quality of castings and help reduce defects [12].

The conditions of martial law in Ukraine affected the organization and duration of experimental work due to restrictions on working hours, curfews, emergency power outages, air raids, logistical difficulties and a shortage of qualified personnel. This complicated the implementation of multi-stage machining operations, 3D printing and assembly of model equipment, and also required more stringent planning of the production process. The impact of these factors was partially compensated by the use of digital control, which ensured the verification of geometry and adjustment of the combination of elements even under unstable conditions of equipment operation.

Prospects for further research are associated with increasing the stability of additive manufacturing of curved blades, expanding the range of materials used and improving hybrid technology for pump impellers. A separate direction is the optimization of digital support of the manufacturing process, covering the stages of design, machining, 3D printing and geometry control. This will allow to reduce the duration of the production cycle and increase the stability of the quality of model equipment.

4. Conclusions

1. A conceptual solution for a hybrid technological scheme for manufacturing model equipment for pump impellers is proposed, in which the base, landing and detachable surfaces are manufactured using the three-axis CNC machining method, and the curved blades and inserts are manufactured using the FDM printing method. This distribution of operations reduces the amount of manual finishing and reduces dependence on five-axis machining centers.

2. A 3D model of a closed pump impeller was built based on the original design documentation, as well as 3D models of model equipment elements. Already at the digital design stage, this made it possible to coordinate the design of the model kit with the subsequent technological route of manufacturing. It also became possible to determine which elements should be manufactured by machining and which by additive manufacturing. This reduced the number of possible errors during subsequent manufacturing and assembly of the equipment, which allows reducing the time for production readjustment.

3. The technology for manufacturing basic elements of model equipment on three-axis CNC milling machines in combination with FDM printing of complex-profile elements has been implemented. It has been established that three-axis CNC machining provides a typical accuracy of base surfaces within 0.15–0.35 mm, FDM printing – 0.1–0.25 mm, and within the framework of the hybrid scheme, an accuracy of 0.1–0.3 mm is achieved. This confirms the feasibility of using mechanical machining for base surfaces, and additive manufacturing – for elements of complex geometry, which allows reducing the amount of manual finishing to 10–15% of the total labor intensity.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, whether financial, personal, authorial or other, which could affect the research and its results presented in this article.

Financing

The research was conducted without financial support.

Data availability

Data will be provided upon reasonable request.

Use of artificial intelligence

ChatGPT (GPT-5.3 model) was needed only to check grammar and punctuation in some places, as well as to preliminarily find sources by keywords. Everything found and corrected was checked by the authors independently. This tool did not affect either the way we did the research, the results, or their explanation. The conclusions were written without it.

Authors' contributions

Pavlo Shelepko: Conceptualization, Methodology, Investigation, Resources, Data curation, Validation, Formal analysis, Visualization, Writing – original draft, Writing – review and editing; ***Olha Ponomarenko***: Conceptualization, Methodology, Supervision, Validation, Formal analysis, Writing – review and editing.

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