Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science. 2026 vol. 28 no. 2 pp. 157–178
ISSN: 1994-6309 (print) / 2541-819X (online)
DOI: 10.17212/1994-6309-2026-28.2-157-178

NSTU NETI

Obrabotka metallov -
Metal Working and Material Science

Journal homepage: http://journals.nstu.ru/obrabotka_metallov

Computer simulation and process engineering for machining thin-walled titanium hemispheres as part of a hybrid robotic module

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ARTICLE INFO

Article history:
Received: 27 March 2026
Revised: 07 April 2026
Accepted: 11 April 2026
Available online: 15 June 2026

Keywords:
Spherical pressure vessel
VT6 titanium alloy (Ti-6Al-4V)
Thin-walled hemisphere
Hybrid equipment
Robotic module
Manufacturing process
Process route sheet
Process tooling and fixtures
Computer simulation
SprutCAM

Funding
This work was supported by the Ministry of Science and Higher Education of the Russian Federation (project FSUN-2026-0005).

ABSTRACT

Introduction. In aerospace engineering, thin-walled titanium spherical pressure vessels for high-pressure helium storage are manufactured by welding two precision-machined hemispheres. The geometric accuracy of the spherical surfaces and weld edge preparation determine leak tightness and service life under operating pressures up to 34 MPa and temperatures down to −196 °C. Due to their low stiffness, thin-walled hemispheres make machining critically dependent on locating charts, clamping forces, and cutting conditions. In the context of *Industry 4.0* and the growing demand for hybrid equipment that integrates mechanical and surface-thermal operations, the development of modular robotic cells providing multifunctional machining with fewer re-clamping operations and increased flexibility has become highly relevant. However, existing design methodologies often fail to account for the multitasking nature, the complexity of preliminary studies, and the requirements for modularity and flexibility. ***The purpose of this work*** is to develop a machining process for thin-walled titanium hemispheres of spherical pressure vessels using computer simulation that ensures compliance with spherical surface accuracy and weld edge preparation requirements, and to improve machining efficiency by minimizing deformation risk, reducing the number of re-clamping operations, and shortening process planning time when integrating the process into a modular robotic cell. **Methods.** Design and manufacturing requirements for the hemispheres were analyzed; cutting conditions were calculated taking into account the specific features of the titanium alloy *Ti-6Al-4V* machining; equipment was selected through a comparative assessment based on production efficiency criteria; and the proposed process was verified in the *SprutCAM* computer-aided process planning (*CAPP*) system, considering equipment kinematics. **Results and Discussion.** Surface finish and accuracy requirements were established: ***Ra*** 0.8 µm for the inner spherical surface and ***Ra*** 3.2 µm for the outer spherical surface. A process route sheet was developed to minimize re-clamping operations and reduce the risk of thin-walled shell deformation. Based on production efficiency criteria, the *DN Solutions PUMA VTS 1214M* vertical turn-mill center was selected, enabling combined turning and milling operations in a single setup, consistent with integral machining on a *CNC* lathe platform. A locating chart using a special ring-type axial clamping fixture was developed and visualized. Machining simulation confirmed the feasibility of the process route, correct setup planning, and the absence of tool–workpiece–fixture collisions, and indicated the potential for rapid process implementation. **Conclusions.** The results contribute to the development of theoretical foundations and conceptual approaches for designing hybrid machine tools that integrate mechanical and surface-thermal processing operations.

For citation: Zhargalova A.D., Skeeba V.Yu., Drach G.A., Morozov A.A., Titova K.A., Papko S.S., Yulusov I.S. Computer simulation and process engineering for machining thin-walled titanium hemispheres as part of a hybrid robotic module. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2026, vol. 28, no. 2, pp. 157–178. DOI: 10.17212/1994-6309-2026-28.2-157-178. (In Russian).

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Introduction

Modern aerospace engineering imposes stringent requirements on high-pressure gas storage systems that operate under extreme thermobaric loading. One of the key structural elements of such systems is the thin-walled titanium spherical pressure vessel (Fig. 1), designed for helium storage at operating pressures up to 34 MPa and cryogenic temperatures down to −196 °C [1]. These products are fabricated by welding two precision-machined hemispheres from the *Ti-6Al-4V* titanium alloy, which offers a favorable combination of high specific strength, corrosion resistance, and adequate weldability [2, 3]. The geometric accuracy of the spherical surfaces and the quality of weld-edge preparation directly govern the joint leak-tightness and service life of the product, rendering the machining operation technologically critical [1, 4].

Fig. 1. Titanium spherical pressure vessel

Thin-walled hemispheres possess reduced stiffness; consequently, the machining process is critically dependent on locating schemes, clamping forces, and cutting conditions. Under unfavorable conditions, elastic deformations, form errors, and deviations in weld-edge preparation arise, complicating subsequent assembly and welding [5–8]. The machining of thin-walled components from titanium alloys has been the subject of investigation for a considerable period, and a substantial body of experimental data has been accumulated to date. A number of researchers [9–12] have convincingly demonstrated that judicious selection of tooling and cutting strategy, while necessary, is far from sufficient. Equally important – and in certain cases even more so – is the proper adjustment of workpiece clamping forces, which to a great extent predetermines the level of forced vibrations and the magnitude of geometric deviations of the finished part. In [13], which addresses the milling of thin-walled *Ti-6Al-4V* components, the emphasis is placed on two interrelated aspects: limiting the radial depth of cut and controlling the heat flux in the tool-workpiece contact zone. Extending this line of inquiry, the authors of [14] investigated the manner in which cutter tooth pitch and cutting parameters shape the temperature field on the surface of a thin-walled workpiece. Comprehensive reviews [15, 16] have systematized the current understanding of the combined effects of vibrations, deformation mechanisms, and geometric errors on the final quality of machined surfaces. The general conclusion drawn in these reviews is that achieving an acceptable outcome requires a comprehensive, rather than fragmented, approach to process control.

The task of machining thin-walled components acquires particular relevance in the context of the ever-growing demand of the machine-tool industry for the development of hybrid machine tools that provide integrated machining on a *CNC* lathe platform. Contemporary requirements for accuracy, productivity, automation, and equipment adaptability – shaped by the digitalization of manufacturing and the Industry 4.0 paradigm – necessitate the creation of methodologies that ensure the optimization of pre-design studies and the design of competitive hybrid metalworking systems [17–20]. As noted in [21–24], hybrid processes that combine mechanical machining with surface-thermal operations (surface hardening, laser-assisted machining) make it possible to substantially enhance the efficiency of the production cycle, reduce the number of operations and reclampings, and improve the surface-layer quality of the parts being machined. The development of theoretical foundations and conceptual approaches to the design of next-generation hybrid equipment that incorporates the integration of mechanical and surface-thermal technologies represents a pressing scientific and practical challenge [25–27].

Under conditions of increasing part complexity, growing demand for multifunctional equipment, and shortened production cycles, the formation of modular robotic production cells constitutes one of the most promising organizational and technological solutions. The contemporary approach to the manufacture of spherical pressure vessels presupposes the establishment of precisely such a cell, combining process operations into a sequence of interlinked modules with automated intra-plant logistics, quality control, and information support [28, 29]. In general terms, the manufacturing route for titanium spherical pressure vessels comprises: material warehousing, blank preparation by cutting, hemisphere forming, quality inspection, machining, and welding.

The warehousing module provides storage of *Ti-6Al-4V-S* titanium alloy sheet stock and its cadenced delivery to downstream operations while maintaining batch traceability. The solution incorporates an automated mono-tower storage system, an unloading station, robotic feeding and handling equipment (a gantry robot *AL-LMH* and a four-axis manipulator), as well as an automated control system [30]. The module output is a sheet semi-finished product prepared for release to the cutting module.

The abrasive waterjet cutting module is intended for the rapid cutting of blanks for hemispheres of the required diameters with minimal thermal impact on the material. The key equipment is an *APW 1530BA* abrasive waterjet cutting machine, together with robotic loading and unloading facilities [31]. Sheet stock of *Ti-6Al-4V-S* enters the module; the output consists of circular blanks directed to the forming module.

The hydraulic deep-drawing module (Fig. 2) performs the forming of hemispheres from circular blanks while ensuring the prescribed geometry and allowances for subsequent operations. The principal equipment includes a vacuum furnace of the *D-9.9.E-13.5UU-IVT-F* type for blank heating, a *YD32-500* hydraulic press for stamping-drawing, and a robotic manipulator for inter-operational transport; *Smart Shelf Hard* cargo racks serve as auxiliary equipment [32]. The module accepts cut discs and produces hemisphere blanks, which are then routed to quality inspection.

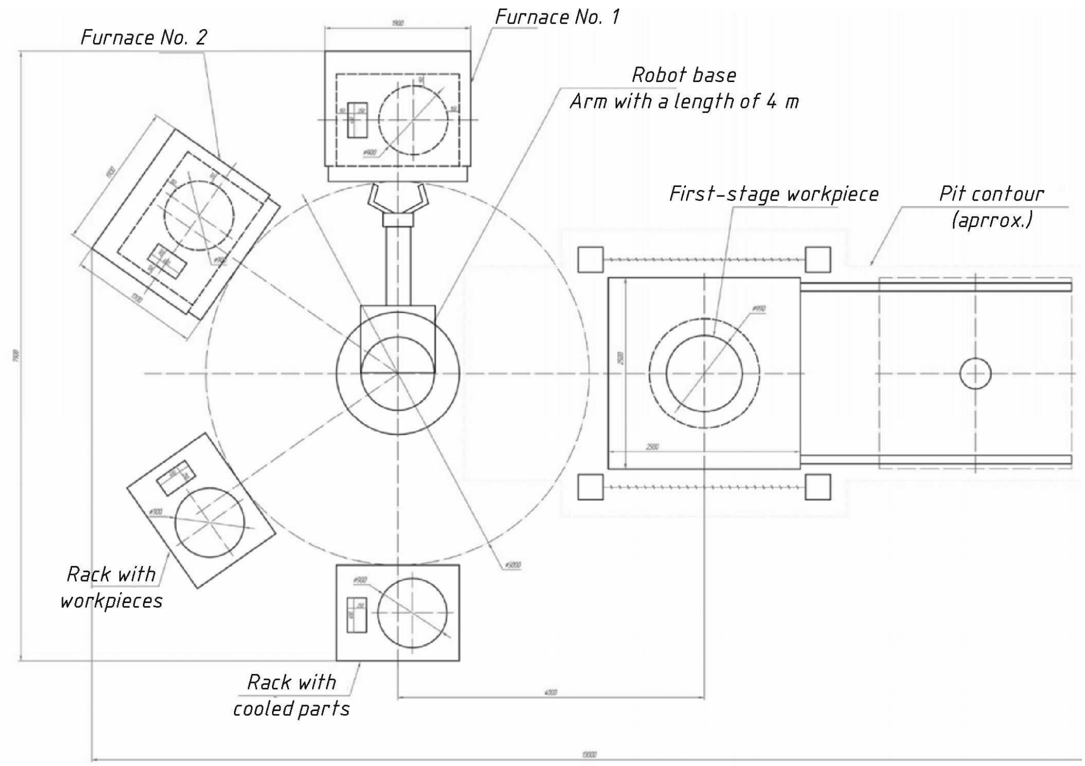

Fig. 2. Layout of the hydraulic deep-drawing module

The quality inspection module (Fig. 3, 4) provides comprehensive verification of semi-finished products and finished items for compliance with technical requirements and renders routing decisions: “conforming”, “for rework”, or “reject”. The core inspection equipment comprises a *USD-60FR* ultrasonic flaw detector and a *GH-800HT* rotary table; automation of inspection operations is ensured by a *KUKA KR 500 R2830* industrial robot and a *KUKA LBR iiwa 11 R1300* collaborative robot with interchangeable grippers [33]. Data processing is supported by dedicated software.

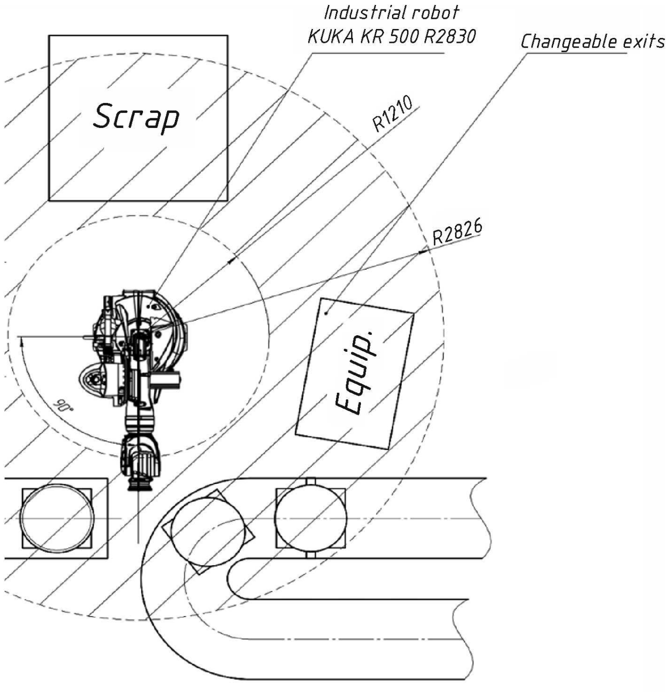

Fig. 3. Quality inspection module, Part 1

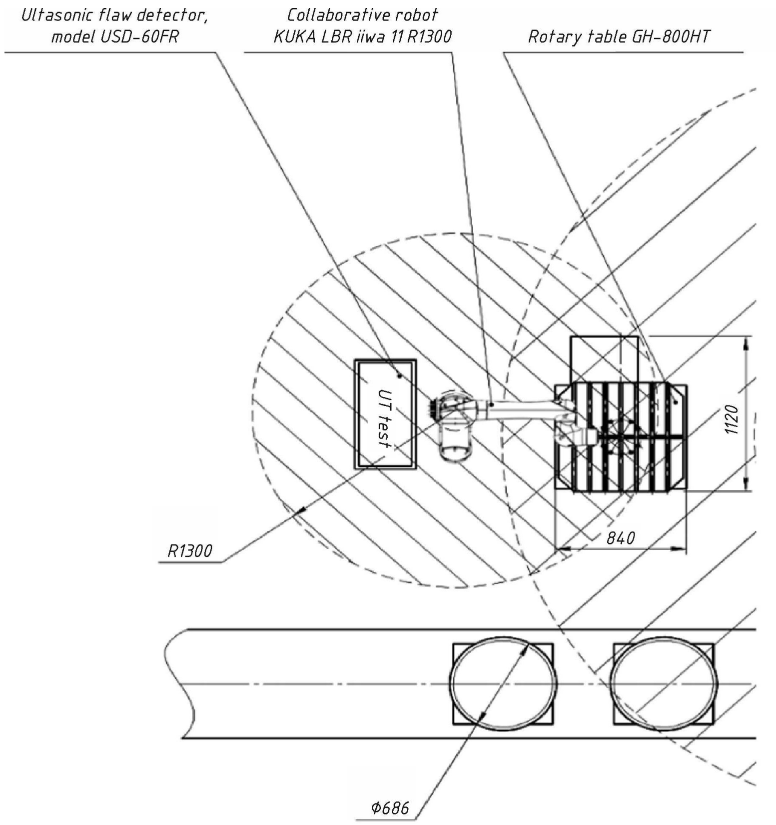

Fig. 4. Quality inspection module, Part 2

The machining module constitutes the link between hemisphere forming and subsequent welding and is responsible for achieving the required accuracy of spherical surfaces, surface-layer quality, and weld-edge preparation. It is precisely this module that forms the subject of the present study.

The welding module carries out assembly and welding operations that yield a leak-tight spherical pressure vessel from two machined hemispheres.

Thus, the machining module is incorporated into the robotic production cell as a technologically critical stage that determines the quality of hemisphere mating in terms of geometry and their readiness for welding. For thin-walled workpieces, the risk of deformation during clamping and cutting, together with the complexity of spatial machining trajectories, renders preliminary process verification by means of computer simulation indispensable [34–36]. The significance of digital simulation is further amplified within the *Digital Twin* paradigm, which provides virtual reproduction of the manufacturing process prior to its physical implementation and integration into the digital infrastructure of the production facility [37–39].

In this context, computer simulation of the machining process constitutes an essential element of process planning. It enables the verification of setups and tool paths, identification of potential tool–workpiece–fixture collisions, assessment of machining completeness and process route feasibility before release to the production environment, thereby reducing the volume of trial runs, lowering the probability of scrap, and enhancing the robustness of integration of the machining module into the robotic production cell for spherical pressure vessel manufacture [40, 41].

It should be emphasized that the present study was carried out within the framework of a research project aimed at developing theoretical foundations and conceptual approaches to the design of hybrid machine tools integrating mechanical and surface-thermal processing operations (project *FSUN-2026-0005*). The disparate use of individual processing technologies leads to an increase in the number of operations, time expenditures, and a decline in machining accuracy; therefore, the creation of a comprehensive approach to the design of hybrid systems – one that unifies modern principles of automation, digital simulation, and machining-parameter prediction – represents a vital task for enhancing the competitiveness of the domestic machine-tool industry [25, 27, 42].

The aim of the present work is to develop a process engineering solution for the machining of thin-walled titanium hemispheres of spherical pressure vessels using computer simulation, ensuring compliance with the requirements for spherical-surface accuracy and weld-edge preparation while improving machining efficiency through a reduction in the risk of deformation, minimization of the number of reclampings, and shortening of process-planning lead time during integration into a modular robotic production cell.

To achieve this aim, ***the following tasks*** were addressed in the course of the study: analysis of design and manufacturing requirements for the hemispheres of spherical pressure vessels and identification of parameters critical to machining; development of a process route sheet; comparative analysis of alternative machine-tool configurations for hemisphere machining and substantiation of the preferred option from the standpoint of integrated machining; formulation of a workpiece locating scheme for the selected equipment; computer simulation of the machining process in the *SprutCAM* system and verification of the proposed process solutions.

Methods

To accomplish the stated objectives, an integrated set of methods was employed, comprising: analysis of the requirements for geometry, surface roughness, leak-tightness, and machining conditions of spherical pressure vessels fabricated from the *Ti-6Al-4V* alloy; calculation of cutting parameters; formulation of equipment selection criteria and comparative evaluation of alternative machine tools against key process performance indicators; and simulation of the manufacturing process in the *SprutCAM* computer-aided manufacturing system.

Two sizes of spherical pressure vessel were considered in the study: 25-liter and 130-liter capacities. For each size, the principal geometric parameters governing the machining requirements and equipment selection were specified. For the 130-liter vessel: hemisphere outer diameter 649 mm, spherical shell thickness 8 mm, nozzle attachment zone diameter 200 mm. For the 25-liter vessel: hemisphere outer diameter 377.5 mm, spherical shell thickness 5 mm, nozzle attachment zone diameter 150 mm. Accordingly, the hemispheres belong to the class of thin-walled shell components for which the wall-thickness-to-diameter ratio is 1.2–1.3%, accounting for their heightened compliance during clamping and machining.

In establishing the requirements for finished hemispheres and developing the working drawings, the following normative documents were employed: requirements for the designation and application of titanium alloys per *GOST 19807-91* [2], surface roughness parameters per *GOST 2789-73* [43], tolerancing of machined dimensions per *GOST 30893.1-2002*, and the general *ESKD* (*Unified System for Design Documentation*) requirements for the preparation of engineering documentation.

In developing the process route sheet for machining, the large hemisphere (130-liter) was selected as the baseline object, since its machining presents a more challenging technological task: the larger diameter and shell thickness demand more rigid workpiece fixturing and gentler cutting conditions aimed at preventing deformations.

Cutting parameters were calculated taking into account the specific characteristics of the *Ti-6Al-4V* titanium alloy, which is characterized by high strength, low thermal conductivity, and a propensity for work hardening of the surface layer – features that necessitate the limitation of cutting speeds and effective heat dissipation [3, 44, 45].

For turning operations, the spindle speed was determined from the relationship:

$$n = 1000\frac{V}{\pi D},$$

where $\boldsymbol{n}$ is the spindle speed, rpm; $\boldsymbol{V}$ is the cutting speed, m/min; $\boldsymbol{D}$ is the machining diameter, mm [46–48].

When milling VT6 titanium alloy, it is necessary to limit the undeformed chip thickness and heat generation: small radial depths of cut ($\boldsymbol{a_e}$) and controlled axial depths ($\boldsymbol{a_p}$) at a sufficient feed per tooth are preferred in order to preclude the rubbing regime, which leads to accelerated tool wear and deterioration of surface quality [14, 49]. The spindle speed for milling was determined by the formula:

$$n = 1000\frac{V}{\pi D_{mill}},$$

where $\boldsymbol{D_{mill}}$ is the cutter diameter, mm [46, 50].

In all operations, copious cutting fluid (coolant) supply was maintained — for the *Ti-6Al-4V* alloy, this is directly linked both to tool life and to the stability of machined-surface quality [44, 45].

To estimate the labor intensity of the process route, relationships for calculating the principal (cutting) time for individual passes were employed. The principal time for turning and drilling operations:

$$t_0 = \left(\frac{L}{Sn}\right)i,$$

where $\boldsymbol{L}$ is the working stroke length, mm; $\boldsymbol{S}$ is the feed, mm/rev; $\boldsymbol{n}$ is the spindle speed, rpm; $\boldsymbol{i}$ is the number of passes.

The principal time for milling operations:

$$t_0 = \frac{L_{\text{traj}}}{F}i,$$

where $\boldsymbol{L_{traj}}$ is the toolpath length, mm; $\boldsymbol{F}$ is the feed rate, mm/min; $\boldsymbol{i}$ is the number of passes.

The arc length for machining a spherical surface was determined using the formula:

$$L = R\varphi,$$

where $\boldsymbol{R}$ is the hemisphere radius, mm; $\boldsymbol{\varphi}$ is the machining angle, rad.

The selection of equipment for the machining module was carried out by comparing three alternative machine tools: *PUMA VTS 1214M* – a vertical turn-mill center [51]; *DN Solutions SMX 5100* – a horizontal turn-mill center with a *Y*-axis; and *EMAG VLC 1200* – a vertical pick-up cell [52]. The selection was based on a system of production-efficiency criteria reflecting the influence of the machine tool on the quality of the thin-walled part, process stability, and total labor intensity. The following criteria were employed in the comparison.

Dimensional margin for the workpiece and tooling. This criterion evaluates the adequacy of the working envelope (machining diameter, height, tool access) in view of the large hemisphere and the fixtures employed. It directly affects the feasibility of toolpaths, the risk of kinematic constraints, and the complexity of setup.

Process stability during machining of a thin-walled shell. This criterion characterizes the propensity of the "machine–fixture–workpiece–tool" technological system toward vibrations and deformations. For a thin-walled hemisphere, this parameter assumes particular importance: it effectively defines the stability limits during the turning of spherical surfaces and, in essence, determines the probability of form or dimensional deviations caused by the compliance of the part itself [5, 10, 16].

Special attention is warranted with regard to *chip evacuation and cutting fluid delivery* – particularly when machining internal surfaces of titanium workpieces. Here, the assessment concerns the effectiveness with which chips can be removed and heat dissipated directly from the cutting zone. The practical significance of this criterion can hardly be overstated: tool life, the risk of localized overheating, and, consequently, the likelihood of surface defects depend directly upon it – which, given the low thermal conductivity of the *Ti-6Al-4V* alloy, is especially critical [44, 45].

Yet another key criterion is *the capability to combine turning with localized milling or drilling* within a single setup. In essence, this concerns the reduction of the number of workpiece reclampings and, correspondingly, the attenuation of cumulative locating errors. This approach aligns directly with the concept of integrated machining on a *CNC* lathe platform – a direction that is being actively advanced in the context of hybrid machine-tool design [21, 25, 42].

Non-productive time: setup, locating, changeover, access, and in-process inspection. This criterion characterizes the labor intensity of preparation and execution of setups. It directly influences productivity and quality consistency during serial execution of the process route.

On the basis of the cumulative criteria, preference is given to equipment that ensures stable turning of spherical surfaces, favorable conditions for chip evacuation during the machining of internal zones, and minimization of the number of reclampings through the combining of operations – which is consistent with the principles of hybrid metalworking system design.

SprutCAM was selected as the software environment for computer-aided manufacturing, since it supports both *NC* program development and virtual verification of turn-mill operations within a unified environment, which is particularly important for the machining of thin-walled titanium hemispheres on a turn-mill center [53]. *SprutCAM* enables the definition of setups and locating schemes, generation of toolpaths with the selection of tools and machining strategies, and machining simulation with due consideration of equipment kinematics. This makes it possible to identify and eliminate potentially hazardous machining zones in advance, thereby reducing the volume of on-machine proving, lowering the probability of scrap, and ultimately enhancing the efficiency of process planning. Furthermore, the system supports post-processing and adaptation to a specific equipment configuration, thus providing a complete preparation cycle from the 3D model to the *NC* code.

Computer-aided process planning for the machining of a thin-walled VT6 titanium alloy hemisphere in the *SprutCAM* system was conducted with the objectives of: verifying the process route feasibility (surface accessibility, correctness of approach and retract moves, completeness of stock removal); generating toolpaths for each machining pass; and obtaining source data for subsequent post-processing and *NC* program preparation [53]. This approach is consistent with contemporary notions of virtual process systems that enable the simulation of tool–workpiece–fixture interactions prior to the physical implementation of the manufacturing process [34, 37, 54].

Results and Discussion

Requirements for accuracy and surface roughness of machined surfaces

Based on the service conditions of spherical pressure vessels (operating pressure up to 34 MPa, cryogenic temperatures) and the design features of the hemispheres, requirements for the surfaces of the finished parts were formulated, dictated by the need to ensure leak-tightness of the welded joint and the structural integrity of the shell in service.

For the hemisphere of the 25-liter spherical pressure vessel (Fig. 5), the following requirements were established. Accuracy requirements for the principal spherical surfaces: inner radius R183.75 ± 0.2 mm; outer radius R188.75 ± 0.3 mm. Accuracy requirements for functional features: nozzle attachment bore Ø150 ± 0.2 mm; wall thickness 5 ± 0.25 mm. Weld edge: the perpendicularity tolerance of the surface relative to datum ***B*** is 0.3 mm. Surface roughness requirements: inner spherical surface – Ra 0.8 μm; outer spherical surface – ***Ra*** 3.2 μm.

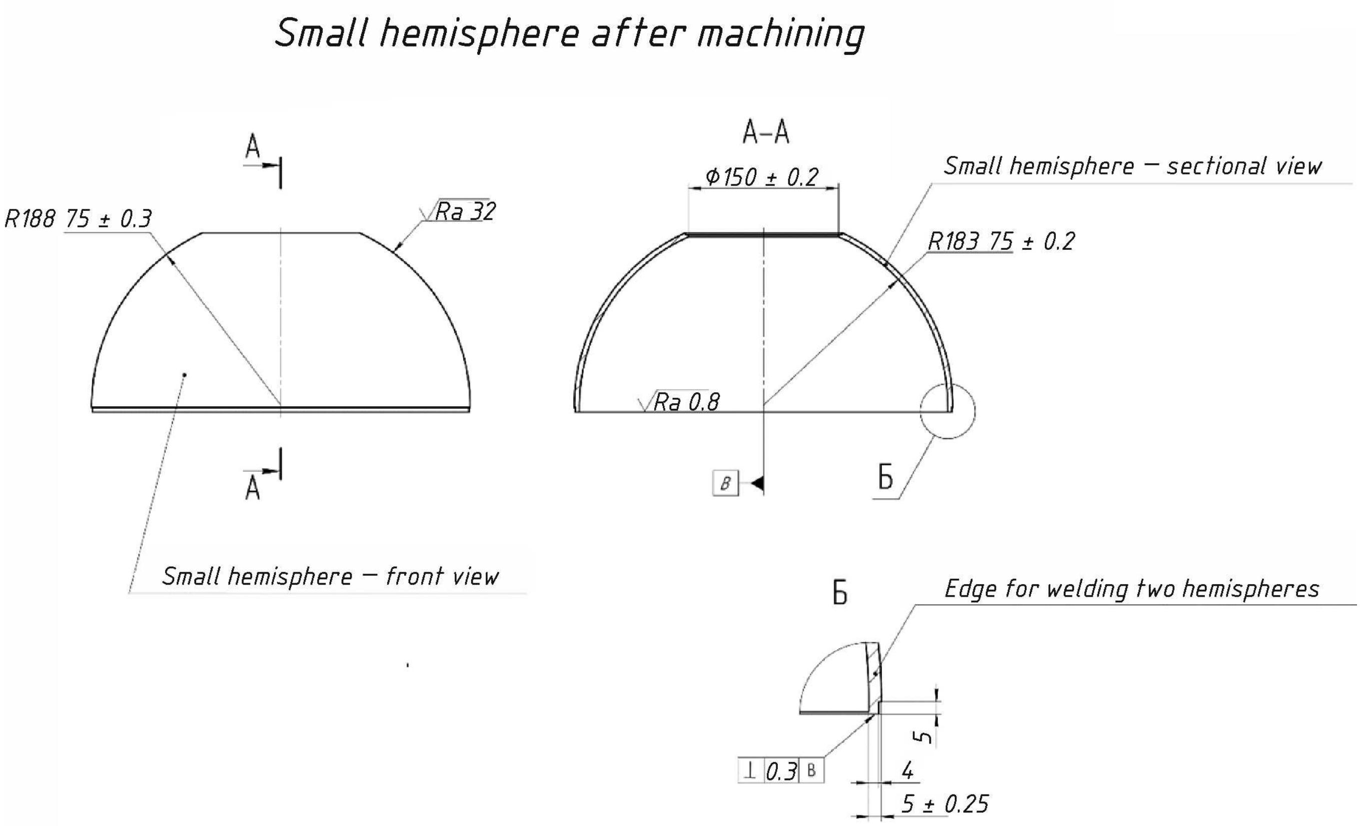

Fig. 5. Small hemisphere: result of machining

For the hemisphere of the 130-liter spherical pressure vessel (Fig. 6), the following requirements were established. Accuracy requirements for the principal spherical surfaces: inner radius R316.5 ± 0.2 mm; outer radius R324.5 ± 0.3 mm. Accuracy requirements for functional features: nozzle attachment bore Ø200 ± 0.2 mm; wall thickness 8 ± 0.25 mm. Weld edge: the perpendicularity tolerance of the surface relative to datum B is 0.3 mm. Surface roughness requirements: inner spherical surface – ***Ra*** 0.8 μm; outer spherical surface – ***Ra*** 3.2 μm.

It should be noted that the more stringent roughness requirement for the inner surface (***Ra*** 0.8 μm versus ***Ra*** 3.2 μm for the outer surface) is dictated by the need to ensure stable gas-flow conditions and to minimize stress concentrators on the inner surface of the shell, which is subjected to high internal pressure. The assigned wall-thickness tolerances (± 0.25 mm) ensure a uniform stress distribution in the thin shell under loading, which is critical for preventing strain localization and failure [1, 5].

Process route sheet and calculation of cutting parameters

On the basis of the calculated cutting parameters and machining pass data, a complete dataset for the process route sheet for the machining of the large hemisphere (130-liter spherical pressure vessel, *Ti-6Al-4V* alloy) was compiled. For each pass, the following parameters were obtained and harmonized: for turning and boring operations – depth of cut t, feed ***S*** (mm/rev), cutting speed ***V*** (m/min), and the calculated spindle speed ***n*** (rpm) for roughing and finishing passes; for milling – radial and axial depths of cut (a_e, a_p), cutting speed ***V***, feed per tooth f_z, and feed rate ***F*** (mm/min); for drilling and center-drilling – feed, cutting speed, and spindle speed sufficient for stable formation of functional features without overheating or galling.

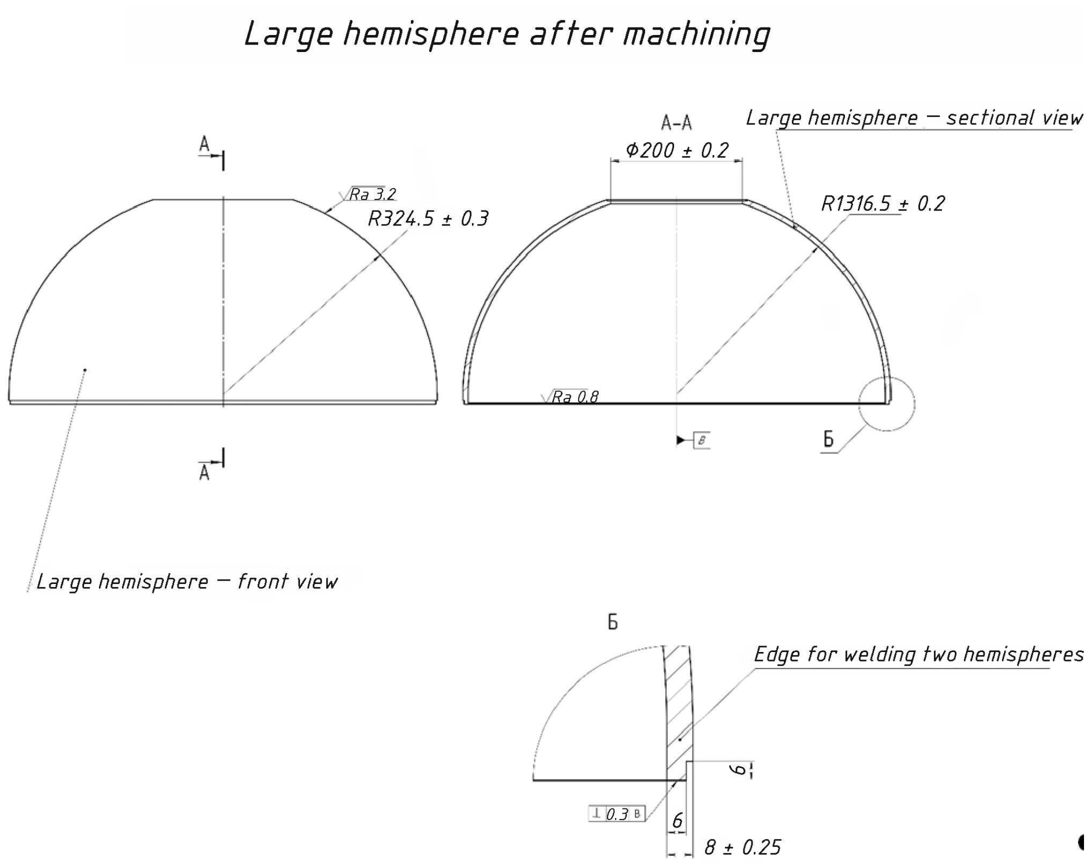

Fig. 6. Large hemisphere: result of machining

Cutting parameters were assigned in accordance with established recommendations for the machining of titanium alloys, as systematized in [44, 45, 55]: limiting the cutting speed during rough turning to 20–30 m/min and during finish turning to 70–80 m/min; ensuring a feed rate that precludes the formation of "zero-thickness" chips and reduces the probability of built-up edge formation; copious cutting fluid supply to compensate for the low thermal conductivity of the alloy.

The obtained cutting-parameter values served as baseline inputs for the automated generation of *NC* programs, toolpath creation, and subsequent setup verification within the *SprutCAM* simulation environment.

As an illustrative example of the data obtained, consider the machining of the inner spherical surface – one of the most labor-intensive and technologically demanding segments of the process route. Within ***Setup 1***, rough and finish machining of the inner spherical surface is performed (Operation 020).

Pass 3 – rough machining of the inner sphere: $\boldsymbol{t}$ = 2.0 mm; $\boldsymbol{S}$ = 0.30 mm/rev; $\boldsymbol{V}$ = 25 m/min; $\boldsymbol{n}$ = 13 rpm; working stroke length $\boldsymbol{L}$ = 414.2 mm; number of passes $\boldsymbol{i}$ = 1. The principal time for this pass was:

$$t_0 = 414.2 \cdot 10.30 \cdot 13 = 106.2 \text{ min.}$$

Pass 4 – finish machining of the inner sphere: $\boldsymbol{t}$ = 1.0 mm; $\boldsymbol{S}$ = 0.15 mm/rev; $\boldsymbol{V}$ = 80 m/min; $\boldsymbol{n}$ = 41 rpm; working stroke length $\boldsymbol{L}$ = 414.2 mm; number of passes $\boldsymbol{i}$ = 1. The calculation yields:

$$t_0 = 414{,}2 \cdot 10{,}15 \cdot 41 = 67{,}35 \text{ min.}$$

In total, the machining of the inner sphere within ***Setup 1*** amounts to 173.55 min. This is arguably one of the most labor-intensive segments of the entire route. The considerable duration is attributable to the combination of two factors: the large diameter of the spherical surface (Ø649 mm) and the cutting-speed limitations inherent to the *Ti-6Al-4V* alloy. Predictably, such cycle duration imposes heightened demands on clamping reliability, process stability, and – no less importantly – chip evacuation. The obtained labor-intensity values provide further confirmation that, given such material-removal volumes, the use of equipment capable of combining operations in a minimum number of setups is advisable.

The rationale for the adopted sequence of passes merits separate clarification. The decision to begin with the inner sphere (***Setup 1***) and only then proceed to the outer surface and weld edges (***Setup 2***) is driven by the objective of minimizing process-induced deformations. The underlying logic is as follows: while the inner cavity is being machined, the workpiece rests with its outer surface against the fixture, thereby providing maximum system rigidity at the most critical stage – the removal of the bulk of the stock.

Selection of machine-tool equipment

Based on the comparison of catalog specifications and the assessment against production-efficiency criteria, the *DN Solutions PUMA VTS 1214M* vertical turn-mill center (Fig. 7) was selected for the machining of the hemispheres. The selection is substantiated by the fact that the vertical configuration provides an assured dimensional margin for a workpiece of the Ø~650 mm class and its associated tooling, improves chip evacuation and cutting fluid delivery during internal machining (chips are removed from the cutting zone by gravity, reducing the risk of re-contact with the machined surface and the tool), and permits the combining of turning and milling passes in a minimum number of setups, which reduces non-productive time and enhances process stability for the thin-walled shell.

Fig. 7. PUMA VTS 1214M machine tool

The adoption of a vertical turn-mill center that enables the integration of diverse machining operations on a single machine platform is consistent with the concept of integrated machining being advanced within the framework of the research project on the development of hybrid machine tools [25, 27, 42]. The multifunctionality of the selected machine permits its consideration as a base platform for the subsequent integration of additional processing technologies, including surface-thermal operations, which represents a promising direction in the evolution of hybrid metalworking systems [21, 22, 24].

In comparison with the alternative options, the *DN Solutions SMX 5100* horizontal turn-mill center, while possessing extended kinematics (*Y*-axis) and offering broader milling capabilities, features a horizontal configuration that is less favorable for chip evacuation during the machining of internal cavities of large thin-walled shells. The *EMAG VLC 1200* vertical pick-up cell is optimized for serial production with automated loading; however, its capacity for combining turning and milling passes is limited, leading to an increase in the number of reclampings.

Workpiece locating scheme

The machining of a thin-walled *Ti-6Al-4V* titanium alloy hemisphere requires a fixturing arrangement that ensures workpiece stability without inducing deformation or damaging the machined surfaces. The specific nature of the thin-walled shell is such that even minor concentrated clamping forces can give rise to localized deformations, producing form errors that exceed the permissible values [5, 8, 56]. As a solution, a special ring-type clamping fixture was adopted, mounted on the machine faceplate and operating on the principle of axial draw-down, which ensures a distributed application of clamping force around the workpiece circumference. For the selected equipment, a workpiece locating scheme was devised (Fig. 8).

Setup is performed on the *PUMA VTS 1214M* machine. The special fixture is secured in the T-slots of the faceplate, with the fixture axis aligned with the spindle axis, and the technological stub of the workpiece is held in boring jaws. This locating scheme ensures the realization of the principle of coincidence between the technological and measurement datums, which minimizes setup error and enhances machining accuracy [57].

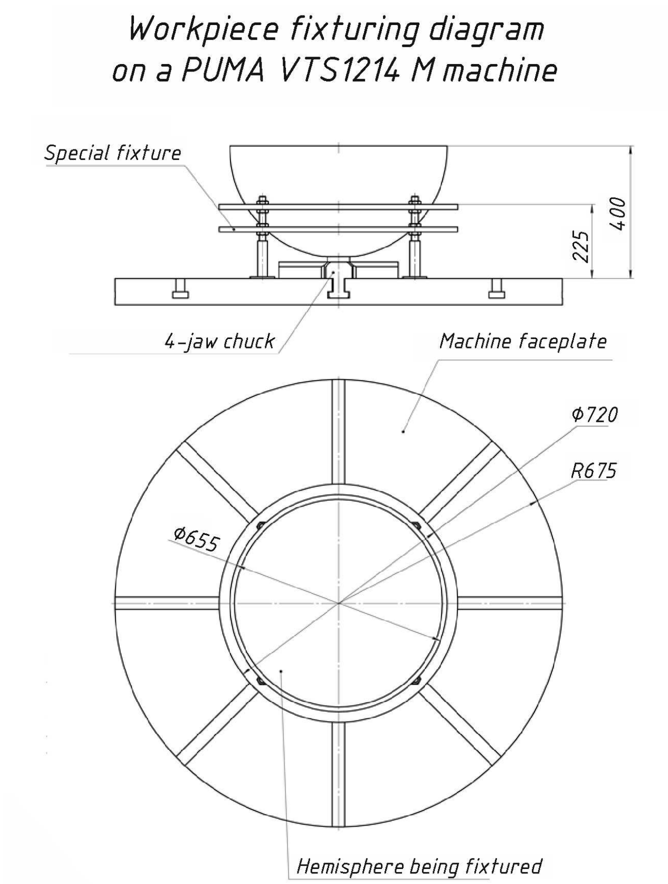

Fig. 8. Workpiece locating (datum) chart

The developed locating scheme accounts for the need to provide tool access to both the inner and outer spherical surfaces, as well as to the weld-edge formation zone. The use of axial draw-down rather than radial clamping makes it possible to eliminate uncontrolled deformations of the thin shell in the radial direction, as corroborated by the results of studies on the optimization of clamping conditions for thin-walled parts [8, 9, 56].

Labor intensity estimation

Following the selection of the locating and clamping scheme, labor intensity was estimated for the fabrication of a single part of the 130-liter spherical pressure vessel. Based on the calculation of principal time per pass, the total principal (cutting) time amounted to $t_{0\Sigma}$ = 437.80 min, or approximately 7.3 hours.

Non-productive time and reclamping durations were taken as follows: setup and clamping in the first setup – t_{setup1} = 12 min; reclamping between the first and second setups – $t_{reclamp}$ = 20 min; part removal after the second setup – t_{unload} = 8 min; in-process inspection upon completion of the second setup – t_{insp} = = 10 min. The total non-productive time amounts to t_{aux} = 50 min, and the total manufacturing time per part is 8 h 13 min.

Analysis of the labor-intensity structure reveals that non-productive time accounts for approximately 10% of the total manufacturing cycle, which attests to the effectiveness of the adopted strategy of combining operations and minimizing the number of reclampings to two. With alternative equipment configurations that do not support combining turning and milling passes, the number of setups increases to three or four, raising non-productive time by 40–60% and increasing the accumulated locating error. This result confirms the advisability of applying the principles of integrated machining on a multifunctional *CNC* machine platform.

Computer simulation in the SprutCAM system

Computer simulation of the machining of the thin-walled hemisphere was performed in the *SprutCAM* system for the purpose of verifying the developed manufacturing process prior to its implementation under production conditions. The simulation environment reproduced the kinematic model of the *PUMA VTS 1214M* machine tool, the geometry of the workpiece and fixtures, and the complete set of cutting tools employed in the process route.

In the course of simulation, the correctness of the selected cutting parameters and toolpaths for all passes in both setups was verified. The machining simulation made it possible to: confirm the feasibility of the process route on the selected equipment; verify the absence of tool–workpiece–fixture collisions at all stages of machining; assess the completeness of stock removal and the correctness of tool approach and retract motions; and visualize the machining process for each setup and pass.

As an illustrative example of successful simulation, consider Pass 10 – ball-nose end milling with a Ø16 mm cutter (Fig. 9). Pass 10 was performed as a 3D machining operation on a portion of the outer hemisphere surface previously occupied by the technological stub (used for workpiece fixation in the first setup). Tool: Ø16 mm ball-nose end mill. The simulation confirmed the correctness of the toolpath, the absence of unmachined zones, and the absence of collisions with fixture elements. The use of a ball-nose end mill ensures smooth profiling of the curved outer-sphere contour while meeting the roughness requirement of ***Ra*** 3.2 µm.

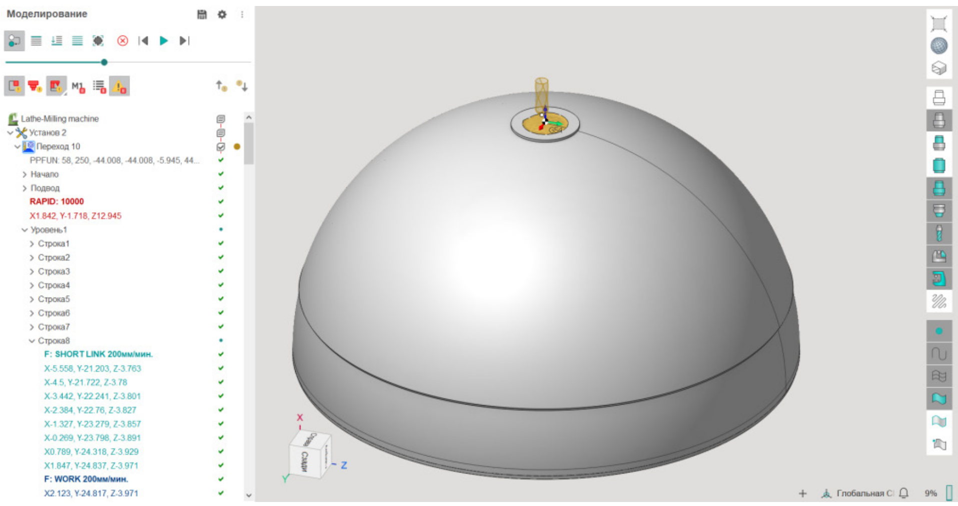

Fig. 9. Simulation of Pass (Operation) 10

Beyond geometric verification, virtual simulation in the *SprutCAM* environment afforded the opportunity to evaluate the kinematics of machine-tool axis motions during the execution of complex spatial toolpaths. For large components with curved profiles, such verification is especially valuable. No collisions between machine elements or instances of axis-travel limit exceedance were detected during simulation, thereby confirming the correctness of the previously adopted decisions regarding the selection of the machine tool and fixtures.

Overall, the results of the virtual simulation attest to the technological feasibility of the developed process route. They may serve as the basis for subsequent post-processing and *NC* program generation. It is also important to emphasize that the constructed virtual process models essentially constitute a fragment of a digital twin of the machining module. In the longer term, this fragment may be embedded within the unified digital space of the robotic production cell for spherical pressure vessel manufacture [37–39].

The results presented herein, considered in the context of hybrid equipment design, lend support to the viability of the proposed approach to process planning for the machining of thin-walled titanium hemispheres. This approach encompasses several interrelated stages: a systematic analysis of technical requirements, a substantiated selection of equipment, the development of a locating scheme, and virtual verification of the process route – and it is precisely their mutual coherence that ensures the integrity of the solution. The approach advances the concept of integrated machining on a *CNC* lathe platform and contributes to the formation of theoretical foundations for the design of hybrid machine tools.

From the standpoint of the advancement of hybrid machining systems, the results obtained are significant in the following respects. First, the fundamental feasibility of performing a complete machining cycle of complex-profiled thin-walled components on a single multifunctional machine tool with minimization of reclampings has been demonstrated – this being a key principle of hybrid equipment [21, 25]. Second, the developed methodology for computer simulation of the manufacturing process can be extended to incorporate surface-thermal operations (induction hardening, laser strengthening), which constitutes the next stage in the development of a hybrid module [22, 24, 27]. Third, the proposed system of equipment selection criteria is applicable not only to the specific case under consideration but also to a broad class of problems in the design of machining modules within hybrid production systems.

A promising avenue for further research is the integration of a surface-thermal treatment module into the process route, which would enable both the mechanical machining of spherical surfaces and the strengthening of functional zones (weld edges, nozzle attachment areas) to be realized on a single machine platform, thereby enhancing the service characteristics of the products and reducing the overall production cycle.

Conclusions

1. A systematic analysis of the design and manufacturing requirements for the fabrication of thin-walled titanium hemispheres of spherical pressure vessels from the *Ti-6Al-4V* alloy was performed, encompassing geometric accuracy, surface roughness, and weld-joint leak-tightness parameters. The parameters critical to machining were established: inner-sphere roughness ***Ra*** 0.8 µm, outer-sphere roughness ***Ra*** 3.2 µm, wall-thickness tolerance ± 0.25 mm, and weld-edge perpendicularity tolerance 0.3 mm. The formulated requirements ensure compliance with leak-tightness conditions under operating pressures up to 34 MPa and cryogenic temperatures down to −196 °C.

2. For all machining passes of the process route for the large hemisphere (Ø649 mm, 130-liter capacity), cutting parameters were calculated and operation labor intensity was estimated, taking into account the specific features of *Ti-6Al-4V* alloy machining (cutting-speed limitations, copious coolant supply). The total principal time amounted to 437.80 min, with a total manufacturing time of 8 h 13 min per part in two setups, confirming the effectiveness of the adopted strategy of combining operations.

3. A comparative selection of machine-tool equipment was conducted using a system of production-efficiency criteria. The preferability of the *DN Solutions PUMA VTS 1214M* vertical turn-mill center was substantiated; this machine enables combining turning and milling passes in a minimum number of setups, provides favorable conditions for chip evacuation during internal machining, and affords a sufficient dimensional margin for the workpiece and fixtures. The selected configuration is consistent with the principles of integrated machining on a *CNC* lathe platform and the concept of hybrid machine tools.

4. To ensure minimal deformation of the thin-walled workpiece, a locating and clamping scheme employing a special ring-type fixture operating on the axial draw-down principle was developed and visualized. The scheme ensures distributed application of clamping force around the workpiece circumference, coincidence of the technological and measurement datums, and tool access to both the inner and outer spherical surfaces.

5. Machining simulation was performed in the *SprutCAM* system: setups were configured, toolpaths were generated, and a simulation-based verification of the process solutions was carried out with due consideration of equipment kinematics. The simulation confirmed the feasibility of the process route, the absence of tool–workpiece–fixture collisions, and the correctness of the setups, and further demonstrated the potential for a significant reduction in process-planning lead time upon implementation. The resulting virtual process models may be regarded as an element of the digital twin of the machining module within the robotic production cell for spherical pressure vessel manufacture.

6. The results of the study contribute to the advancement of theoretical foundations and conceptual approaches to the design of hybrid machine tools integrating mechanical and surface-thermal processing operations. A promising direction is the integration of surface-thermal treatment into the process route on a single machine platform, which would enhance the service characteristics of the products and reduce the overall production cycle.

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Conflicts of Interest

The authors declare no conflict of interest.