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Intelligent decision support system for the optimization of turning parameters of thin-walled parts in the context of designing hybrid metal-cutting equipment

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ABSTRACT

Introduction. Machining of thin-walled parts represents one of the most challenging problems in modern mechanical engineering, particularly in the aerospace industry, precision instrumentation, and other high-technology sectors where requirements for geometric accuracy are critical. The low bending stiffness of such structures causes extreme sensitivity to the forces arising during machining: elastic deformations induced by the combined action of cutting forces and clamping forces lead to significant deviations from specified dimensions and shape, constituting one of the primary causes of manufacturing defects. Conventional methods of cutting parameter selection, based on reference data and operator experience, do not provide the capabilities for quantitative prediction of thin-walled workpiece deformation behavior and fail to account for the specifics of their deformation behavior. This problem is particularly relevant in the context of developing next-generation hybrid machine tools integrating mechanical and surface-thermal technological operations, where scientifically based selection of machining parameters is an essential condition for ensuring the required product quality. ***The purpose of the present work*** is to develop, implement in software, and comprehensively verify an intelligent decision support system (*DSS*) prototype designed for the scientifically based selection of optimal turning parameters to minimize elastic deformation of thin-walled parts as an integral component of a design methodology for hybrid metal-cutting systems. **Research methods.** The system is based on an analytical mathematical model establishing the functional relationship between cutting parameters, the resultant cutting force, and the elastic deflection of the workpiece, calculated using the cantilever beam model. An iterative multi-parameter optimization algorithm with the objective function of minimizing maximum deflection was implemented. Verification of system effectiveness was conducted on two representative thin-walled parts – a bushing made of *steel 45* and a ring made of *AK9ch* aluminum alloy – through comprehensive simulation that included: verification of process technological feasibility in the *SprutCAM CAM* system and evaluation of deformation fields via static finite element analysis in the *ANSYS Mechanical CAE* system. **Results and discussion.** Application of the developed *DSS* provided a significant reduction in force exerted on the workpiece: the tangential cutting force component decreased by a factor of 2.1 for the steel bushing and by a factor of 10.8 for the aluminum ring. Finite element analysis confirmed a reduction in maximum elastic deformation of 72.3% (from 0.0602 to 0.0167 mm) for the steel bushing and of 87.9% (from 0.0422 to 0.0051 mm) for the aluminum ring. A key technological result is that deformation values after optimization do not exceed the design tolerances for cylindricity. *SprutCAM* simulation confirmed the complete technological feasibility of the machining processes. The obtained results demonstrate the prospects of integrating intelligent decision-making systems into the design methodology of hybrid machine tools to enhance the competitiveness of the domestic machine tool industry.

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Introduction

Thin-walled parts, characterized by a diameter-to-wall-thickness ratio exceeding 15, are key structural elements in the aerospace industry, precision instrumentation, power engineering, and other knowledge-intensive sectors that impose critical requirements on weight reduction while simultaneously ensuring high geometric accuracy [1–3]. The widespread use of such parts in modern structures is driven by the trend toward lighter and more functional products; however, their manufacture entails considerable technological challenges governed by the fundamental specifics of the mechanical behavior of these structures.

The principal problem in the machining of thin-walled parts is their extremely low bending stiffness, which causes pronounced sensitivity to external force effects [4, 5]. During turning, the workpiece is subjected to the simultaneous action of several groups of force factors: cutting forces generated by the tool during surface formation, clamping forces exerted by the workholding fixtures, and, in certain cases, inertial forces due to workpiece rotation. The combined action of these factors gives rise to elastic deformations that may exceed the permissible deviations in form and dimensions specified in the design documentation [6, 7]. This results in a high rate of manufacturing rejects, an increased number of finishing operations, and, ultimately, a significant increase in production costs.

Conventional methods of cutting parameter assignment, based on reference standards and the empirical experience of process engineers, were developed for machining rigid workpieces and do not account for the deformation behavior of thin-walled structures [8, 9]. These methods operate with productivity and tool life criteria but do not incorporate an assessment of the workpiece deformation response, which fundamentally limits their applicability to the class of parts under consideration. Moreover, the very process of clamping a thin-walled workpiece in a jaw chuck introduces an initial deformation whose shape and magnitude are determined by the design of the clamping device, the number of jaws, and the force application scheme [10, 11].

The aforementioned problem assumes particular significance in the context of the growing demand of the modern machine tool manufacturing industry for the development of next-generation hybrid machine tools that integrate mechanical and surface-thermal technological operations [12–33]. Contemporary requirements for accuracy, productivity, automation, and adaptability of process equipment under conditions of production digitalization and implementation of the *Industry 4.0* concept necessitate the creation of methodological approaches that ensure optimization of both preliminary design studies and the actual design process for competitive hybrid metalworking systems [34, 35]. Given the increasing structural complexity of machined parts, the growing demand for multifunctional equipment, and the objective shortening of production cycles, it becomes imperative to integrate advanced technologies – surface-thermal treatment, robotics, and digital control — into machine tool systems [36, 37]. However, existing methodological approaches to design frequently fail to account for the multitasking nature of such systems, the complexity of their development at the preliminary design stage, and the need to ensure modularity and flexibility of the configuration [38].

The fragmented application of different machining technologies leads to an increase in the number of operations and workpiece refixturing, an increase in time and material costs, an accumulation of locating errors, and, consequently, a reduction in machining accuracy [39]. For instance, in the conventional organization of a manufacturing process that includes mechanical machining and surface-thermal hardening operations performed on separate equipment, material deformations during thermal exposure and refixturing errors necessitate increased inter-operational allowances reaching 30–40% of the specified depth of the hardened layer [40]. Therefore, the development of a comprehensive approach to the design of hybrid systems, combining modern principles of automation, digital modeling, and machining parameter prediction, constitutes a pressing scientific and practical challenge whose resolution is of strategic importance for enhancing the competitiveness of the domestic machine tool industry.

One of the key elements in the design methodology for hybrid equipment is the creation of intelligent tools that provide scientifically substantiated assignment of technological machining parameters, taking into account the specifics of particular part types and their manufacturing conditions. With respect to thin-walled parts, this implies the need for systems capable of quantitatively predicting the workpiece deformation response and directionally optimizing machining parameters to minimize geometric distortions.

In recent decades, numerical and algorithmic methods have been actively developed to address the problem of deformation control during machining of thin-walled parts. Simulation of the machining process using the finite element method (*FEM*) in *CAE* systems such as *ANSYS* and *ABAQUS* enables detailed analysis of stress and strain fields, providing valuable information for process adjustment [41, 42]. A number of researchers [43, 44] have demonstrated the effectiveness of finite element modeling for predicting thermomechanical deformations during machining of thin-walled parts made from aluminum and titanium alloys. However, a full-scale *FEM* analysis requires substantial computational resources and specialized expertise, which significantly constrains the possibilities of its operational use under the conditions of manufacturing process planning.

An alternative research direction involves the application of mathematical optimization algorithms – genetic algorithms, swarm intelligence methods, and simulated annealing algorithms – to search for optimal combinations of cutting parameters [45–47]. The effectiveness of these methods has been demonstrated for solving multi-criteria technological optimization problems, including the simultaneous minimization of surface roughness and maximization of machining productivity. Nevertheless, metaheuristic algorithms often operate on a "black-box" principle, failing to provide the user with a transparent and physically interpretable justification for the proposed solutions [48]. This circumstance diminishes the level of confidence in the generated recommendations on the part of process engineering personnel and impedes the practical deployment of such systems.

Several researchers have attempted to develop comprehensive decision support systems for process engineering that integrate physical process models with optimization algorithms. In [49], an architecture for an expert system for the selection of machining conditions based on production rules was proposed; however, the static nature of the knowledge base limits the system's adaptability. Studies [50, 51] demonstrated the potential of neural network models for predicting force parameters and deformations during machining; however, the requirements for large training datasets and the non-interpretability of results remain significant limitations.

Thus, the analysis of the current state of the scientific problem reveals the need for a hybrid intelligent tool that would combine the computational speed of analytical calculations, the transparency of a physics-based mathematical model, the purposefulness of algorithmic optimization, and the possibility of rigorous verification of results by numerical modeling. Such a tool, on the one hand, addresses a specific technological challenge – optimization of machining parameters for thin-walled parts – and, on the other hand, forms an element of an intelligent subsystem suitable for integration into hybrid machine tool equipment implementing the concept of digital manufacturing.

The present study continues and substantially extends the ideas established in the earlier work by *Zhargalova A.D.* and *Eremeykin P.A.* [52], devoted to the conceptual architecture of a software system for the selection of rational turning parameters for thin-walled parts. The preceding research was primarily focused on the formulation of a system architecture based on production rules and the development of a modular concept that laid the methodological foundation for this research direction. The present work achieves a significant advancement in several directions: at the theoretical level, an analytical mechanical model based on cantilever beam theory has been constructed, establishing a quantitative functional relationship between cutting parameters and the elastic deformation of the workpiece; at the algorithmic level, an iterative multi-parameter optimization algorithm with a clearly defined parameter adjustment strategy and convergence criteria has been developed and implemented; at the software implementation level, a fully functional prototype of a web-based system has been created, integrating a knowledge base on materials and tools, a computational engine, and an optimization module; at the verification level, a cross-platform validation strategy has been implemented, combining *CAM* simulation of the manufacturing process and static finite element analysis of deformations.

The purpose of this work is the algorithmic implementation and comprehensive computational verification of an intelligent decision support system prototype for the scientifically substantiated selection of optimal turning parameters for thin-walled parts, considered as a constituent element of the design methodology for hybrid metalworking systems.

To achieve the stated purpose, the following ***objectives*** were addressed:

– formulation of an analytical mathematical model establishing the functional relationship between cutting parameters and elastic deformation of a thin-walled workpiece;

– development and software implementation of an iterative multi-parameter optimization algorithm for cutting parameters with an objective function targeting minimization of maximum deflection;

– creation of a prototype web-based *DSS* with a graphical user interface; verification of system effectiveness through *CAM* simulation of the manufacturing process and static finite element analysis of deformations for representative thin-walled parts made from structural materials.

Methods

Mathematical model of the thin-walled workpiece deformation response

The accuracy of surface generation during turning of thin-walled parts is largely governed by the magnitude of the radial cutting force component F_y, which induces bending deflection of the workpiece in the direction normal to the machined surface [53]. For quantitative assessment of this deformation, the developed system employs a simplified yet physically grounded cantilever beam model that analytically relates the cutting parameters to the geometric outcome of machining.

Calculation of the force parameters of the cutting process is performed on the basis of classical empirical relationships adapted for the analysis of the deformation response [54, 55]. The tangential (principal) cutting force component F_z is determined by:

$$F_z = C_p \cdot t^x \cdot s^y \cdot V^n \cdot K_{fr}, \quad (1)$$

where t is the depth of cut (mm); s is the feed rate (mm/rev); V is the cutting speed (m/min); C_p, x, y, n are empirical coefficients determined by the properties of the workpiece material, tool geometry, and machining conditions;

K_{fr} is a correction factor accounting for the actual mechanical properties of the workpiece material.

The radial F_y and axial F_x cutting force components are determined through established proportional relationships with the tangential component [56]:

$$F_x \approx 0.35 \cdot F_z, \quad (2)$$

$$F_y \approx 0.45 \cdot F_z. \quad (3)$$

The specific values of the proportionality coefficients are determined by the machining conditions and tool geometry and are stored in the system's knowledge base.

Prediction of the maximum elastic deflection δ_{max} of the thin-walled workpiece, modeled as a cantilever beam clamped at the chuck end, is performed using the formula:

$$\delta_{max} = \frac{F_y \cdot L^3}{3 \cdot E \cdot I},$$

where L is the design length of the cantilevered workpiece section (mm); E is the elastic modulus of the material (MPa); I is the second moment of area of the cross-section (mm^4).

For the annular cross-section characteristic of the class of parts under consideration, the second moment of area is given by:

$$I = \frac{\pi}{64} \cdot (D^4 - d^4),$$

where D is the outer diameter of the workpiece; d is the inner diameter of the workpiece.

Despite the simplifying assumptions (neglecting rotational motion of the workpiece, non-uniformity of load distribution along the machining length, and dynamic effects), this model provides an adequate estimate of the order of magnitude of the deformation and its dependence on the process parameters, as confirmed by extensive experimental data [57, 58]. A fundamental advantage of the analytical model is its minimal computation time, enabling its deployment within the iterative optimization algorithm in real time.

Architecture of the intelligent system

The developed intelligent *DSS* is implemented as a modular architecture, the schematic diagram of which is presented in Fig. 1. The system comprises four principal functional blocks: a knowledge base on materials and tools, a calculation module, an optimization module, and a web-based user interface.

The knowledge base contains structured information on empirical coefficients for cutting force calculation, physical and mechanical properties of structural materials (elastic modulus, ultimate tensile strength, yield strength, hardness), characteristics of cutting tools, and reference recommendations for assignment of initial machining parameters. The calculation module implements the computational procedures for determining force parameters and the deformation response in accordance with the described mathematical model.

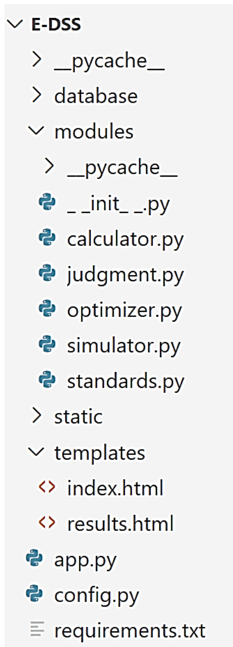


Fig. 1. Component architecture of the intelligent decision support system

The modular architecture of the system is fully consistent with the design principles for hybrid machine tool equipment, which presuppose flexibility of design solutions, adaptability to a wide range of manufacturing tasks, and the possibility of functional upgrading. In the future, this system can be integrated as a control software module within the digital subsystem of a hybrid machine tool complex, providing adaptive assignment of machining parameters with due consideration of the actual workpiece condition and current machining environment.

Iterative optimization algorithm

The core of the system is an iterative multi-parameter optimization algorithm whose objective is to determine the set of parameters $\boldsymbol{V}$, $\boldsymbol{s}$, $\boldsymbol{t}$ that minimizes the objective function $\boldsymbol{\delta_{max}}$ while simultaneously satisfying the technological constraints on the permissible ranges of machining parameters. The flowchart of the algorithm is presented in Fig. 2.

The algorithm commences by assigning initial (starting) cutting parameters based on reference standards [59] stored in the system's knowledge base. For this set of parameters, the force characteristics of the process and the predicted workpiece deformation are calculated in accordance with the described mathematical model. Subsequently, the admissibility condition is verified:

$$\delta_{max} \le \delta_{admissibility},$$

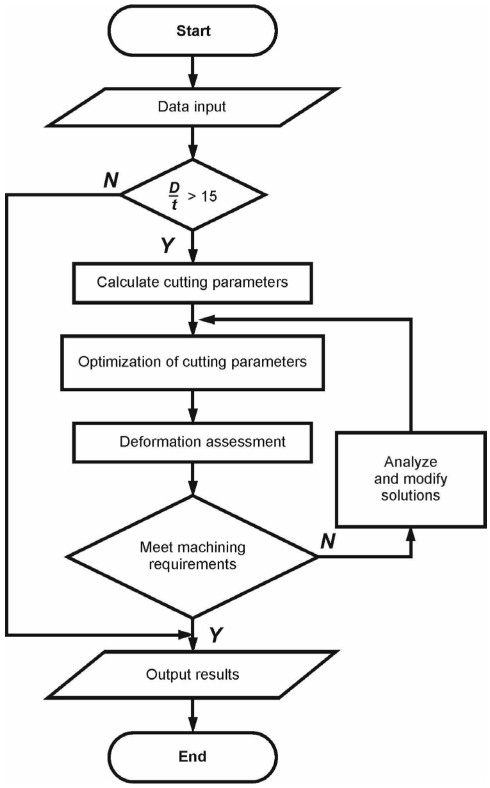


Fig. 2. Flowchart of the intelligent system's algorithm

where $\boldsymbol{\delta}_{admissibility}$ is the permissible deformation derived from the design tolerance on the form (cylindricity) of the machined part.

If this condition is not satisfied, the algorithm proceeds to the stage of iterative parameter adjustment aimed at reducing the radial cutting force component $\boldsymbol{F}_y$. The adjustment strategy is based on a sensitivity analysis of the objective function with respect to each of the controlled parameters. As follows from the empirical cutting force formula, the depth of cut $\boldsymbol{t}$ enters the expression with the highest exponent $\boldsymbol{x}$ (typical values $\boldsymbol{x}$ = 1.0 … 1.2), which determines its dominant influence on the magnitude of the force effect. Accordingly, reducing the depth of cut constitutes the most effective control lever. The algorithm implements a sequential reduction of $\boldsymbol{t}$ and $\boldsymbol{s}$ with a concurrent minor adjustment of $\boldsymbol{V}$ until the admissibility criterion $\boldsymbol{\delta}_{max} \leq \boldsymbol{\delta}_{admissibility}$ is satisfied.

The physical rationale of the optimization strategy consists in transitioning to so-called "gentle" cutting regimes [60], characterized by reduced instantaneous force loading on the workpiece while maintaining the technological feasibility of the process. This approach finds a direct analogy with the task of optimizing process parameters in hybrid machining systems, where harmonization of the mechanical and surface-thermal treatment conditions is required to ensure the desired product characteristics [61].

User interface structure

To ensure convenient interaction between the process engineer and the developed system, an intuitive web-based interface has been created using modern front-end technologies (*HTML5*, *CSS3*, *JavaScript*) in conjunction with a server-side component built on the *Flask* (*Python*) microframework. The interface structure is presented in Fig. 3.

The interface is logically divided into three principal functional zones. The parameter input panel is intended for specifying the initial data required for calculations: geometric parameters of the workpiece (outer and inner diameters, machining length, and wall thickness), selection of the workpiece material from the built-in database, and specification of accuracy requirements – the permissible deformation magnitude or form tolerance (cylindricity). The output and evaluation panel displays, in a structured tabular format, both the initial and optimized cutting parameters, calculated values of all cutting force components, and

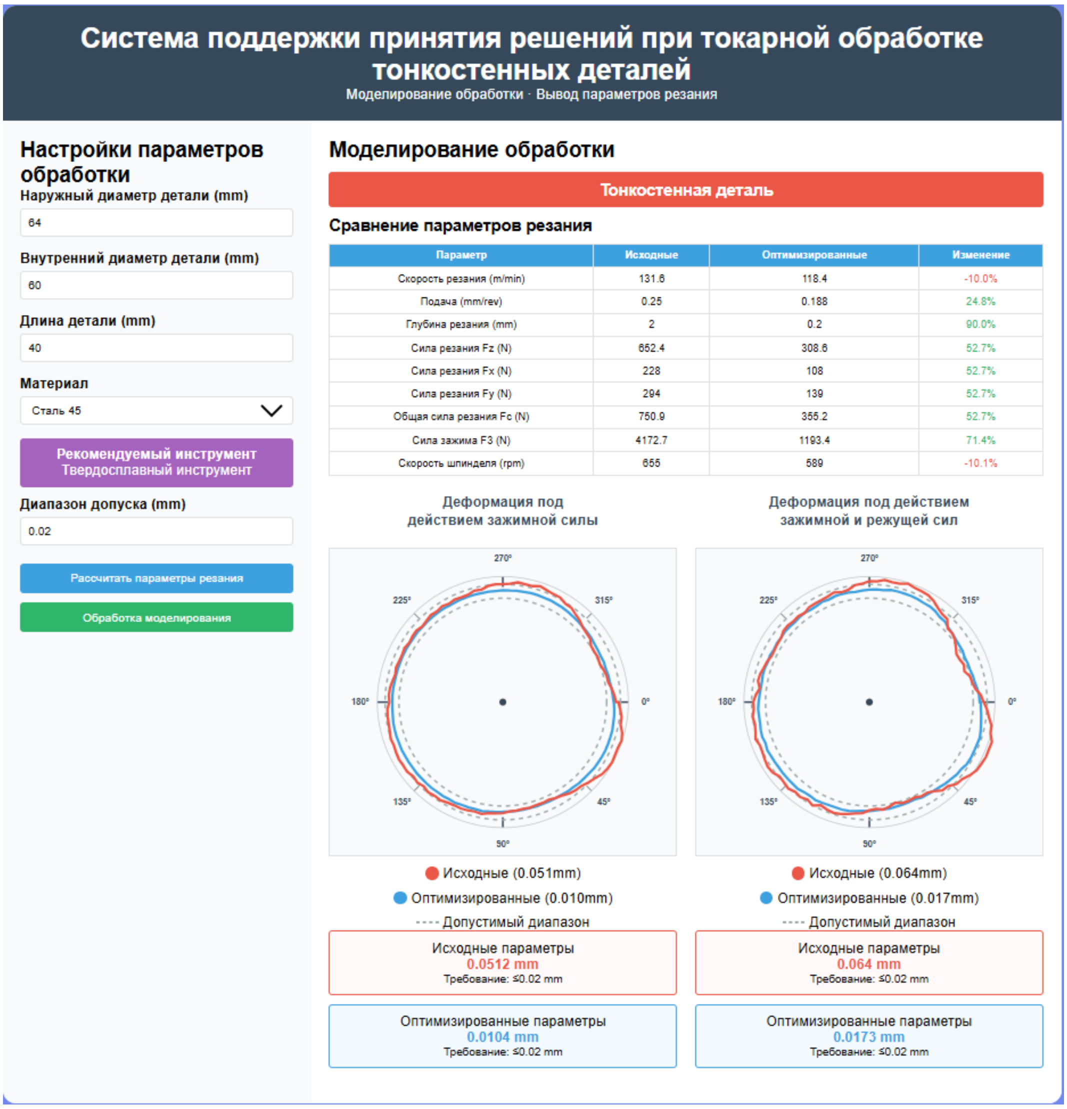


Fig. 3. Structure of the intelligent decision support system user interface

the required clamping force. This panel also includes automatic classification of the part by the thin-wall criterion based on the diameter to wall thickness ratio. The results visualization area is intended for graphical presentation of the algorithm outcomes, including the display of the final calculated deformation value and its compliance with the specified tolerance.

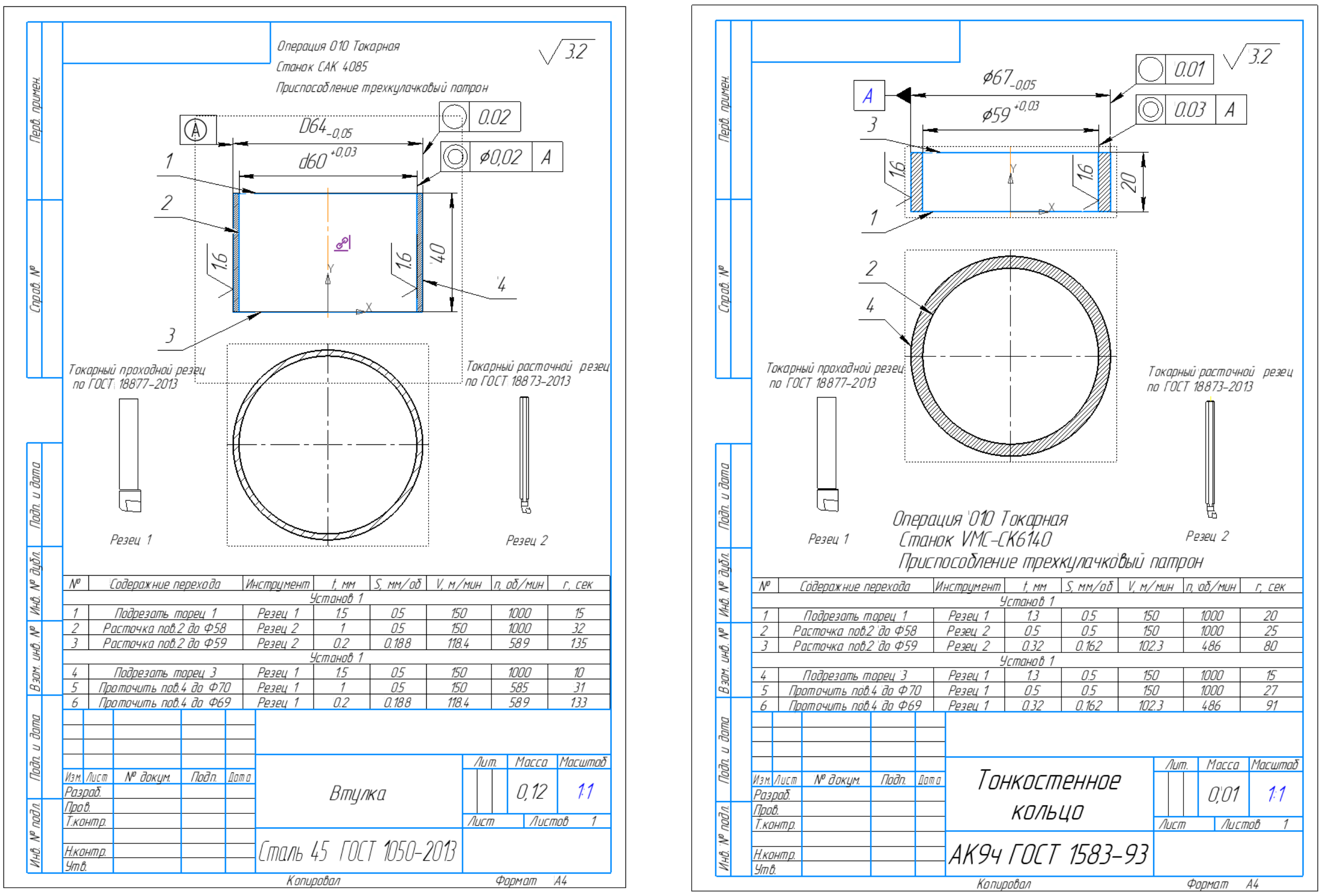
This interface structure minimizes data preparation time, ensures transparency of the optimization process, and forms an objective basis for informed technological decision-making. Integration of the client-side component with the server-side calculation and optimization modules ensures a high system response speed.

Objects of study

Two representative thin-walled parts (Fig. 4) were selected for testing and verification of the developed *DSS*, representing different structural materials and exhibiting different geometric parameters:

Part 1 – bushing made of *steel 45*: outer diameter 64h9 mm, inner diameter 60H8 mm, length 40 mm, wall thickness 2 mm, diameter-to-wall-thickness ratio 32, cylindricity tolerance 0.02 mm. Workpiece material – medium-carbon structural *steel 45* with an elastic modulus $\boldsymbol{E}$ = 200 GPa.

Part 2 – ring made of aluminum alloy *AK9ch*: outer diameter 69h9 mm, inner diameter 59H8 mm, length 20 mm, wall thickness 4 mm (5 mm on one side), diameter-to-wall-thickness ratio 17.3, cylindricity tolerance 0.01 mm. Workpiece material – casting aluminum alloy *AK9ch* with an elastic modulus $\boldsymbol{E}$ = 71 GPa.



a *b*

Fig. 4. Working drawings of the study objects:

a – bushing made of *steel 45*; *b* – ring made of *AK9ch* aluminum alloy

The selection of these objects was determined by the need to evaluate the versality of the system with respect to materials possessing substantially different physical and mechanical properties (the elastic modulus of steel exceeds that of the aluminum alloy by nearly a factor of three), as well as to parts exhibiting different degrees of thinness of walls.

Comprehensive verification methodology

Verification of the effectiveness of the optimized cutting parameters was conducted according to a two-level scheme providing a comprehensive assessment of the proposed solutions.

At the first level (technological verification), *CAM* simulation was performed in the *SprutCAM* environment. Virtual machining of the workpieces was carried out to verify the technological correctness of the control programs generated for *CNC* lathes *CAK4085* and *VMC-CK6140*. During simulation, the following were monitored: correctness of the tool path, completeness of stock removal, and absence of collisions between the tool, workpiece, and machine tool components.

At the second level (deformation verification), static finite element analysis was performed in the *ANSYS Static Structural* environment. Mesh models of the investigated parts were created, to which force loads corresponding to both the initial (reference) and optimized cutting parameters were applied. Clamping forces in a three-jaw chuck and the radial cutting force component were modeled. The *FEM* analysis methodology conforms to modern approaches to modeling of process-induced deformations validated in [62, 63]. This verification strategy provides a comprehensive evaluation of the proposed solutions both from the standpoint of their technological feasibility and from the perspective of guaranteeing the required geometric accuracy, which is of fundamental importance for the design of advanced hybrid machine tool equipment.

Results and Discussion

Cutting parameter optimization results

The developed intelligent *DSS* demonstrated a consistent and technologically justified optimization strategy aimed at a radical reduction of the instantaneous force load on the thin-walled workpiece. A comparative analysis of the initial (reference) and optimized cutting parameters, together with the corresponding force factors for both study objects, is summarized in Table.

Comparative analysis of cutting parameters and force factors before and after optimization

Parameter	Bushing (steel 45)		Ring (AK9ch)	
	Initial	Optimized	Initial	Optimized
Cutting speed V, m/min	131.6	118.4	126.0	102.3
Feed rate s, mm/rev	0.25	0.188	0.20	0.162
Depth of cut t, mm	2.00	0.20	2.00	0.32
Spindle speed n, rpm	655	589	599	486
Tangential force F_z, N	652.4	308.6	161.6	15.0
Axial force F_x, N	228.0	108.0	57.0	5.0
Radial force F_y, N	294.0	139.0	73.0	7.0
Total cutting force F, N	750.9	355.2	186.1	17.3
Clamping force F_c, N	4172.7	1193.4	1298.4	161.0

Analysis of the data presented in Table reveals several fundamentally important patterns.

The dominant change in both cases is a radical reduction in the depth of cut: by a factor of 10 for the steel bushing (from 2.0 to 0.2 mm) and by a factor of 6.25 for the aluminum ring (from 2.0 to 0.32 mm). This is a direct consequence of the mathematical model: the depth of cut enters the force calculation formula with the highest exponent, making it the most effective control parameter. The feed rate was reduced by 24.8 % and 19.0 %, respectively, providing additional reduction in force loads. The cutting speed was adjusted only slightly (reductions of 10.0 % and 18.8 %), since this parameter enters the formula with the lowest exponent and its influence on the cutting force is comparatively minor.

The combined effect of the described adjustments resulted in a reduction of the total cutting force by a factor of 2.1 for the steel bushing (from 750.9 to 355.2 N) and by a factor of 10.8 for the aluminum ring (from 186.1 to 17.3 N). The substantial difference in the degree of reduction is explained by the difference in the values of the empirical coefficients for steel and aluminum alloy: the higher sensitivity of the aluminum alloy to changes in the depth of cut ensures a proportionally greater reduction in the force effect.

A fundamentally important ancillary outcome of the optimization is a proportional reduction in the required clamping force F_c, calculated according to the methodology for ensuring reliable workpiece fixation [64]: by a factor of 3.5 for the steel bushing and by a factor of 8.1 for the aluminum ring. This result carries independent technological significance, since the clamping force constitutes an independent source of thin-walled workpiece deformation [10, 11]. The reduction in clamping force creates an additional margin for minimizing the initial deformation of the workpiece caused by non-uniform radial compression in the jaw chuck.

The obtained results confirm the validity of the selected algorithmic strategy, based on the prioritized reduction of the depth of cut, and are consistent with the general scientific approach to the formation of “gentle” machining conditions described in [60, 65]. It should be noted that the transition to “gentle” conditions inevitably entails an increase in the number of passes required to ensure complete stock removal; however, in the context of thin-walled part machining, this increase is compensated by a fundamental improvement in geometric accuracy and a reduction in the scrap rate.

Finite element analysis results

Static *FEM* analysis in the *ANSYS* environment provided quantitative confirmation of the effectiveness of the proposed optimization strategy. Comparative deformation fields for both study objects under the initial and optimized machining parameters are presented in Fig. 5.

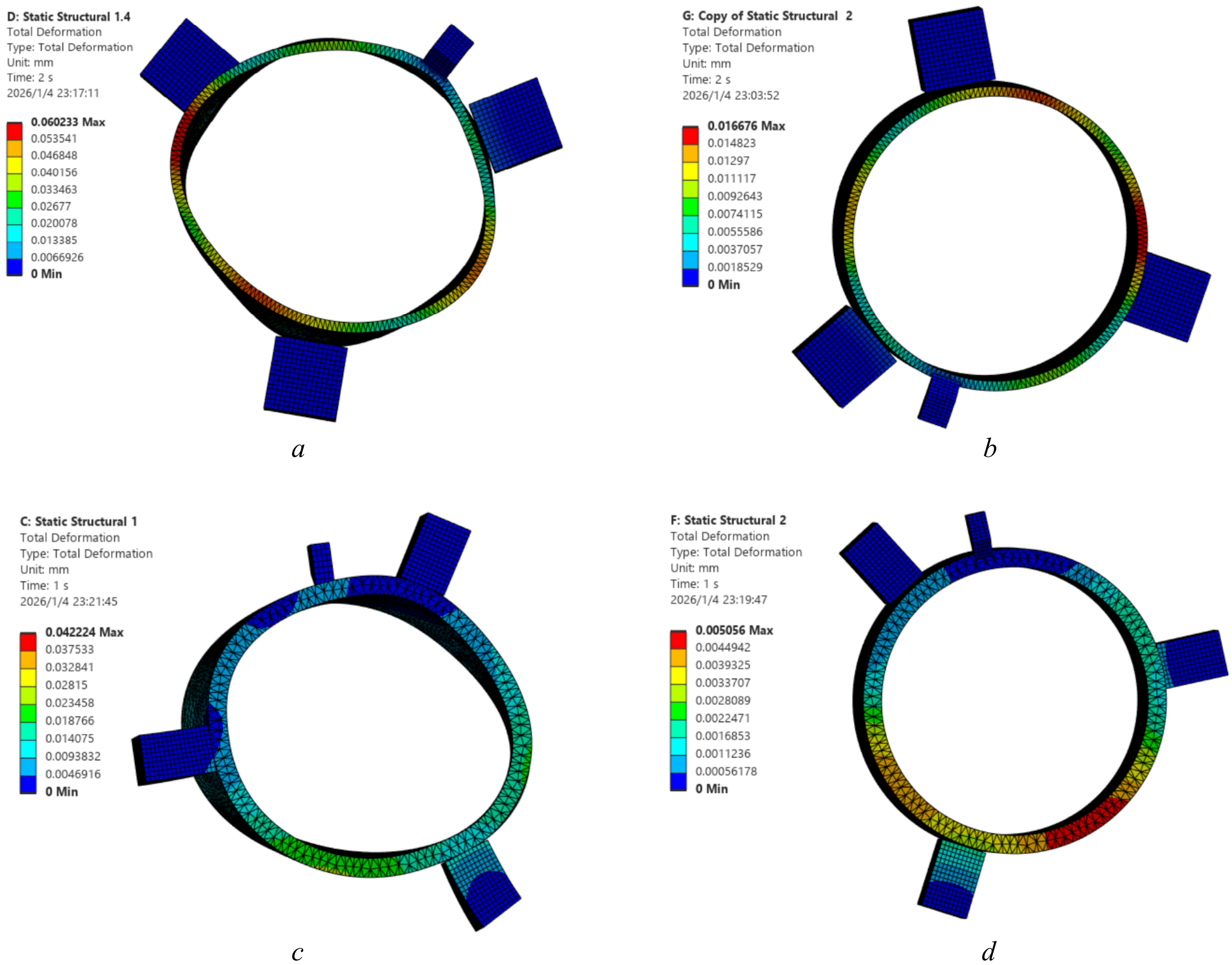


Fig. 5. Comparison of deformation fields obtained in *ANSYS*:

a – deformations of the steel bushing with initial parameters; *b* – deformations of the steel bushing with optimized parameters; *c* – deformations of the aluminum ring with initial parameters; *d* – deformations of the aluminum ring with optimized parameters

For the steel bushing, the maximum elastic deformation decreased from 0.0602 mm (under initial parameters) to 0.0167 mm (under optimized parameters), representing a relative reduction of 72.3%. For the aluminum ring, the analogous reduction was from 0.0422 mm to 0.0051 mm, i.e., 87.9%. Visual analysis of the deformation fields (Fig. 5) clearly demonstrates not only a decrease in the absolute magnitude of the maximum deflection, but also a substantial contraction of the zone of maximum deformations, indicating a more uniform stress distribution within the workpiece body under the optimized conditions.

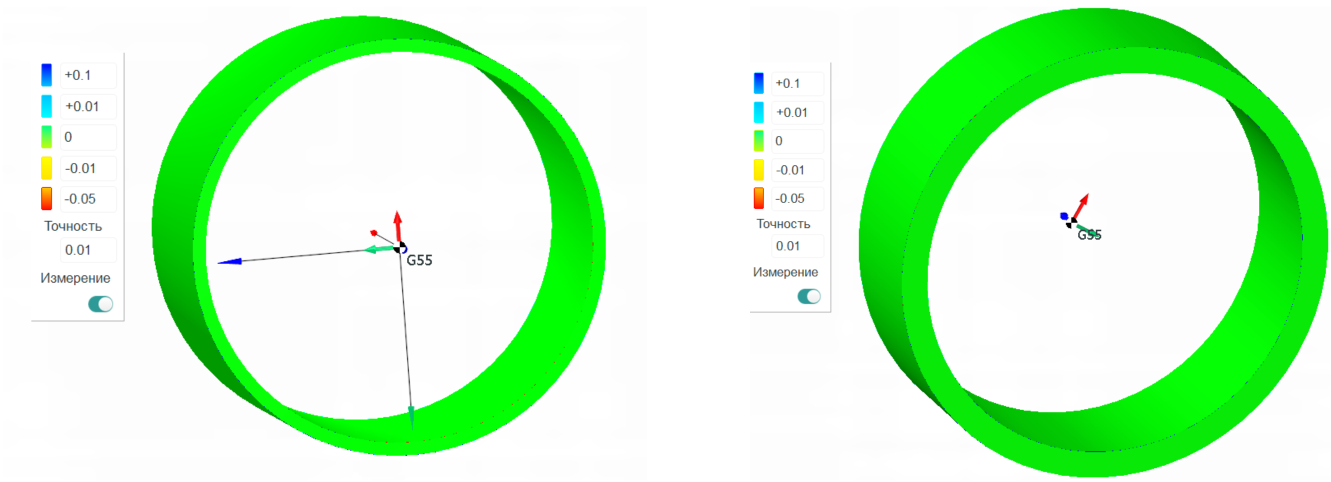
The most significant technological result is the comparison of the post-optimization deformation values with the design tolerances for cylindricity. For the steel bushing, the obtained value $\boldsymbol{\delta}_{max}$ = 0.0167 mm does not exceed the cylindricity tolerance of 0.02 mm. For the aluminum ring, the value $\boldsymbol{\delta}_{max}$ = 0.0051 mm likewise falls within the tolerance of 0.01 mm. This result is of principal importance: it demonstrates that the developed system is capable of generating not merely improved, but technologically sufficient machining parameters that guarantee compliance with the design requirements for form accuracy.

The substantially higher optimization effectiveness for the aluminum ring (87.9% versus 72.3%) is explained by a combination of physical and mechanical and geometric factors. The aluminum alloy is characterized by a lower elastic modulus, which causes greater sensitivity of the deformation response to changes in the force parameters. Furthermore, the greater wall thickness of the ring (4 mm versus 2 mm) provides an increased second moment of area of the cross-section, amplifying the effect of force load reduction on the resultant deformation.

It should be noted that the *FEM* analysis results establish a lower bound on the achievable accuracy, since the model accounts for static loads but does not incorporate several additional factors: dynamic cutting force components, thermal deformations, tool wear, and imperfect workpiece locating. Nevertheless, the obtained quantitative estimates possess considerable practical value for preliminary analysis of technological capabilities and substantiation of design decisions during the development of manufacturing processes, including in the context of hybrid machine tool equipment design.

CAM simulation results

Virtual machining in the *SprutCAM CAM* system (Fig. 6) confirmed full technological feasibility of the processes constructed on the basis of the optimized *DSS* recommendations.



a *b*

Fig. 6. Results of virtual machining in *SprutCAM*:
a – simulation of bushing machining (*steel 45*); *b* – simulation of ring machining (*AK9ch* aluminum alloy)

For both study objects, tool motion trajectories were correctly generated, complete stock removal was ensured, and collisions between the tool and machine tool components were eliminated. Analysis of the trajectories demonstrated that the optimized parameters fall within the technological capabilities of the *CAK4085* and *VMC-CK6140* lathes, confirming the practical applicability of the proposed solutions.

Discussion in the context of hybrid equipment design

The developed *DSS* formalizes the process of searching for “gentle” machining conditions by linking them directly to the expected geometric outcome through a quantitative assessment of workpiece deformation. This fundamentally distinguishes the proposed approach from existing methods based on empirical tables or “black-box” optimization algorithms and is consistent with the global trend toward the development of scientifically substantiated methods for accuracy control of manufacturing processes [66, 67].

The obtained results demonstrate that directional optimization of cutting parameters using analytical models can be no less effective for controlling deformations of thin-walled parts than increasing the complexity of fixture design [68], and should be considered as the first and mandatory stage of manufacturing process planning. This conclusion is of particular significance for the tasks of hybrid machine tool equipment design, where the integration of intelligent machining parameter control systems allows compensating for limitations imposed by the structural complexity of multifunctional machine tool systems.

In the context of the research project on the development of theoretical foundations and conceptual approaches to the design of hybrid machine tool equipment integrating mechanical and surface-thermal technological operations, the present study contributes in several directions. First, the methodology for the development of intelligent subsystems providing scientifically substantiated assignment of mechanical machining parameters has been demonstrated; this methodology can be extended to combined (hybrid) processes involving simultaneous or sequential mechanical and surface-thermal treatments. Second, the proposed *DSS* architecture, based on the integration of physics-based mathematical models, optimization algorithms, and verification procedures, forms the prototype of a digital twin of the manufacturing process – a key element of the *Industry 4.0* concept and intelligent manufacturing [69–71]. Third, the obtained quantitative data on the dependence of the deformation response of thin-walled workpieces on machining parameters create a foundation for the design of adaptive control systems for hybrid equipment capable of adjusting parameters in real time on the basis of feedback from sensor monitoring systems.

A promising direction for the further development of the *DSS* is its extension to account for thermal deformations arising from the integration of surface-thermal operations (induction hardening, laser treatment) into a unified processing cycle with mechanical machining. Such an extension would require the inclusion of temperature fields and thermoelastic deformations in the mathematical model; however, the proposed system architecture supports such scaling without fundamental redesign of the algorithmic framework.

Certain limitations of the present study should also be noted, as they define the directions for future work. System verification was performed exclusively by means of computer simulation; for definitive confirmation of result validity, full-scale experiments with measurement of actual deformations of machined parts are required. The mathematical deformation model is based on the simplified cantilever beam model, which does not account for the three-dimensional nature of deformation in real parts and may introduce errors when machining parts with complex geometry. Furthermore, the current version of the system does not account for dynamic effects (vibrations, self-excited oscillations), which may exert a significant influence during machining of ultra-thin-walled parts with wall thicknesses below 1 mm.

Conclusion

As a result of the conducted research, a methodology for the intelligent selection of turning parameters for thin-walled parts has been developed and verified, implemented as a prototype of a web-based decision support system founded on the integration of analytical physics-based mathematical modeling of the deformation response, an iterative multi-parameter optimization algorithm, and cross-platform verification procedures in *CAM*/*CAE* environments.

The key element of the system is the optimization algorithm, which simultaneously and coherently adjusts all principal process parameters – depth of cut, feed rate, and cutting speed – in the direction of minimizing the objective function (maximum elastic deflection of the workpiece) while satisfying constraints on the permissible parameter ranges. The algorithm implements a strategy of prioritized reduction of the depth of cut as the parameter with the greatest force effect, ensuring a coordinated decrease in both cutting forces and the required clamping force.

For the test parts – a bushing made of *steel 45* and a ring made of aluminum alloy *AK9ch* – application of the algorithm resulted in a reduction of the total cutting force by factors of 2.1 and 10.8, respectively, and of the clamping force by factors of 3.5 and 8.1. Static finite element analysis in *ANSYS* quantitatively confirmed a reduction in the maximum calculated elastic deformation by 72.3 % (from 0.0602 to 0.0167 mm) for the steel bushing and by 87.9 % (from 0.0422 to 0.0051 mm) for the aluminum ring. A critically important technological outcome is that the post-optimization deformation values do not exceed the design tolerances for cylindricity (0.02 mm and 0.01 mm, respectively), demonstrating the system's capability to generate technologically sufficient machining parameters. *CAM* simulation in *SprutCAM* confirmed complete technological correctness of the generated control programs.

The conducted study demonstrates that a systematic approach combining analytical calculation, algorithmic optimization, and simulation modeling enables the transition from empirical assignment of cutting parameters to a scientifically substantiated one, thereby creating a foundation for improving the machining accuracy of thin-walled parts, reducing the scrap rate, and shortening the manufacturing process planning time. The obtained results constitute an element of an intelligent subsystem suitable for integration into next-generation hybrid machine tool equipment combining mechanical and surface-thermal technological operations, and contribute to the development of the methodology for creating competitive hybrid metalworking systems meeting the requirements of *Industry 4.0*.

References

1. Bolsunovskiy S., Vermel V., Gubanov G., Kacharava I., Kudryashov A. Thin-walled part machining process parameters optimization based on finite-element modeling of workpiece vibrations. *Procedia CIRP*, 2013, vol. 8, pp. 276–280. DOI: 10.1016/j.procir.2013.06.102.

2. Goryachkin B.S., Chernata N.S. Obzor vozmozhnykh variantov ispol'zovaniya tekhnologii i materialov 3D-pechati v aviatsionnoi promyshlennosti [Review of possible applications of 3D printing technologies and materials in the aviation industry]. *E-SCIO*, 2021, no. 5 (56), pp. 657–682. (In Russian).

3. Qi S., Yan S., Xu J., Sun Y. Predictive modeling of deformation induced by residual stress for thin-walled parts in double-sided alternating precision turning. *Journal of Manufacturing Processes*, 2025, vol. 146, pp. 19–29. DOI: 10.1016/j.jmapro.2025.04.085.

4. Fomenko R.N., Timofeev M.V. Optimizatsiya tekhnologicheskikh uslovii obrabotki tonkostennykh detalei iz alyuminievykh splavov s tsel'yu snizheniya ostatochnykh deformatsii [Technological conditions optimization for aluminum alloy thin-walled parts machining to decrease residual deformations]. *Vestnik Bryanskogo gosudarstvennogo tekhnicheskogo universiteta = Bulletin of Bryansk State Technical University*, 2018, no. 4, pp. 4–11. DOI: 10.30987/article_5b28d1921f23d8.29887997.

5. Sun H., Zhao J., Zheng Z., Jiang Y., Jin X., Deng S., Tang Y., Zhang X. A review of the deformation mechanism and control of low stiffness thin-walled parts. *CIRP Journal of Manufacturing Science and Technology*, 2025, vol. 60, pp. 322–355. DOI: 10.1016/j.cirpj.2025.05.007.

6. Yadav M.H., Mohite S.S. Controlling deformations of thin-walled Al 6061-T6 components by adaptive clamping. *Procedia Manufacturing*, 2018, vol. 20, pp. 509–516. DOI: 10.1016/j.promfg.2018.02.076.

7. Liu G., Wang Y., Huang B., Ding W. The intelligent monitoring technology for machining thin-walled components: A review. *Machines*, 2024, vol. 12 (12), p. 876. DOI: 10.3390/machines12120876.

8. Markov V.V., Smetannikov A.V., Kiskeev P.I., Lebedeva L.I., Vetchinnikov D.A. *Raschet rezhimov rezaniya. Kursovoe i diplomnoe proektirovanie po tekhnologii mashinostroeniya* [Calculation of cutting modes. Course and thesis design in machine building technology]. Moscow; Vologda, Infa-Engineering Publ., 2023. 136 p. ISBN 978-5-9729-1465-4.

9. Ikhries I.I., Al-Shawabkeh A.F., Haddad J.S., Al-Najdawi N.A., Alfaqs F.A. Integrated multi-objective optimization for high-precision CNC turning of 7075 aluminum alloy. *Next Materials*, 2025, vol. 9, p. 101338. DOI: 10.1016/j.nxmate.2025.101338.

10. Serkov A.S., Masyagin V.B., Artyukh R.A., Serkova L.B., Akimov V.V. Issledovanie napryazhenno-deformirovannogo sostoyaniya zagotovki zubchatogo kolesa s primeneniem matematicheskikh modelei v zavisimosti ot sil zazhima v trekhi shestikulachkovykh samotsentriruyushchikh patronakh [Studying stress-strain state of gear billet using mathematical models depending on clamping forces in 3 and 6 cam self-centering chucks]. *Omskii nauchnyi vestnik = Omsk Scientific Bulletin*, 2020, no. 4 (172), pp. 13–18. DOI: 10.25206/1813-8225-2020-172-13-18.

11. Arbuzov E.V., Zhargalova A.D., Lazarenko G.P., Semisalov V.I. K voprosu o deformatsii tonkostennykh detalei pri obrabotke na stankakh tokarnoi gruppy [On deformation of thin-walled parts while turning on the lathes]. *Nauka i obrazovanie = Science and education*, 2014, no. 2, pp. 36–48. DOI: 10.7463/0214.0700319.

12. Grzesik W., Ruszaj A. *Hybrid manufacturing processes – Physical fundamentals, modelling and rational applications*. Cham, Springer, 2021. 234 p. ISBN 978-3-030-77106-5. eISBN 978-3-030-77107-2. DOI: 10.1007/978-3-030-77107-2.

13. Skeeba V.Yu., Vakhrushev N.V., Titova K.A., Chernikov A.D. Ratsionalizatsiya rezhimov poverkhnostnoi zakalki VEN TVCh rabochikh poverkhnostei puansona v usloviyakh gibridnoi obrabotki [Rationalization of modes of HFC hardening of working surfaces of a plug in the conditions of hybrid processing]. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2023, vol. 25, no. 3, pp. 63–86. DOI: 10.17212/1994-6309-2023-25.3-63-86.

14. Lv J., Tang R., Jia S., Liu Y. Experimental study on energy consumption of computer numerical control machine tools. *Journal of Cleaner Production*, 2016, vol. 112 (5), pp. 3864–3874. DOI: 10.1016/j.jclepro.2015.07.040.

15. Skeeba V., Ivancivsky V., Chernikov A., Martyushev N., Vakhrushev N., Titova K. Design and technological aspects of integrating multi-blade machining and surface hardening on a single machine base. *Journal of Manufacturing and Materials Processing*, 2024, vol. 8 (5), p. 200. DOI: 10.3390/jmmp8050200.

16. Makarov V.M., Lukina S.V. Unikal'naya sinergiya gibridnykh stankov [Unique synergy of hybrid machines]. *Ritm: Remont. Innovatsii. Tekhnologii. Modernizatsiya = RITM: Repair. Innovation. Technologies. Modernization*, 2016, no. 8, pp. 18–25.

17. Skeeba V.Yu., Ivancivsky V.V. Povyshenie effektivnosti poverkhnostno-termicheskogo uprochneniya detalei mashin v usloviyakh sovmeshcheniya obrabatyvayushchikh tekhnologii, integriruemykh na edinoi stanochnoi baze [Improving the efficiency of surfacethermal hardening of machine parts in conditions of combination of processing technologies, integrated on a single machine tool base]. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2021, vol. 23, no. 3, pp. 45–71. DOI: 10.17212/1994-6309-2021-23.3-45-71.

18. Ryzhikova T.N., Borovskii V.G. Issledovanie strategicheskikh perspektiv modernizatsii stankostroeniya [Exploring the strategic perspectives for machine tool industry modernization]. *Ekonomicheskii analiz: teoriya i praktika = Economic Analysis: Theory and Practice*, 2017, vol. 16, no. 5, pp. 835–850. DOI: 10.24891/ea.16.5.835.

19. Martino J.P. Technological forecasting – An overview. *Management Science*, 1980, vol. 26 (1), pp. 28–33. DOI: 10.1287/mnsc.26.1.28.

20. Mitsuishi M., Ueda K., Kimura F. *Manufacturing systems and technologies for the new frontier.* The 41st CIRP Conference on Manufacturing Systems, May 26–28, Tokyo, 2008. London, Springer-Verlag, 2008. 556 p. e-ISBN 978-1-84800-267-8. DOI: 10.1007/978-1-84800-267-8.

21. Fernando W.L.R., Karunathilake H.P., Gamage J.R. Strategies to reduce energy and metalworking fluid consumption for the sustainability of turning operation: A review. *Cleaner Engineering and Technology*, 2021, vol. 3, p. 100100. DOI: 10.1016/j.clet.2021.100100.

22. Ivancivsky V.V., Skeeba V.Yu. *Gibridnoe metalloobrabatyvayushchee oborudovanie. Tekhnologicheskie aspekty integratsii operatsii poverkhnostnoi zakalki i abrazivnogo shlifovaniya* [Hybrid metal working equipment. Technological aspects of integrating the operations of surface hardening and abrasive grinding]. Novosibirsk, NSTU Publ., 2019. 348 p. ISBN 978-5-7782-3988-3.

23. Lauwers B., Klocke F., Klink A., Tekkaya A.E., Neugebauer R., Mcintosh D. Hybrid processes in manufacturing. *CIRP Annals*, 2014, vol. 63 (2), pp. 561–583. DOI: 10.1016/j.cirp.2014.05.003.

24. Moriwaki T. Multi-functional machine tool. *CIRP Annals – Manufacturing Technology*, 2008, vol. 57 (2), pp. 736–749. DOI: 10.1016/j.cirp.2008.09.004.

25. Brecher C., Özdemir D. *Integrative production technology: Theory and applications*. Springer International Publ., 2017. 1100 p. ISBN 978-3-319-47451-9. e-ISBN 978-3-319-47452-6. DOI: 10.1007/978-3-319-47452-6.

26. Yamazaki T. Development of a hybrid multi-tasking machine tool: Integration of additive manufacturing technology with CNC machining. *Procedia CIRP*, 2016, vol. 42, pp. 81–86. DOI: 10.1016/j.procir.2016.02.193.

27. Skeeba V.Yu. Gibridnoe tekhnologicheskoe oborudovanie: povyshenie effektivnosti rannikh stadii proektirovaniya kompleksirovannykh metalloobrabatyvayushchikh stankov [Hybrid process equipment: improving the efficiency of the integrated metalworking machines initial designing]. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2019, vol. 21, no. 2, pp. 62–83. DOI: 10.17212/1994-6309-2019-21.2-62-83.

28. You K., Yan G., Luo X., Gilchrist M.D., Fang F. Advances in laser assisted machining of hard and brittle materials. *Journal of Manufacturing Processes*, 2020, vol. 58, pp. 677–692. DOI: 10.1016/j.jmapro.2020.08.034.

29. Sun S., Brandt M., Dargusch M.S. Thermally enhanced machining of hard-to-machine materials – A review. *International Journal of Machine Tools and Manufacture*, 2010, vol. 50 (8), pp. 663–680. DOI: 10.1016/j.ijmachtools.2010.04.008.

30. Kim S.-G., Lee C.-M., Kim D.-H. Plasma-assisted machining characteristics of wire arc additive manufactured stainless steel with different deposition directions. *Journal of Materials Research and Technology*, 2021, vol. 15, pp. 3016–3027. DOI: 10.1016/j.jmrt.2021.09.130.

31. Lee Y.-H.; Lee C.-M. A study on optimal machining conditions and energy efficiency in plasma assisted machining of Ti-6Al-4V. *Materials*, 2019, vol. 12, p. 2590. DOI: 10.3390/ma12162590.

32. Lee C.M., Kim D.H., Baek J.T., Kim E.-J. Laser assisted milling device: A review. *International Journal of Precision Engineering and Manufacturing-Green Technology*, 2016, vol. 3 (2), pp. 199–208. DOI: 10.1007/s40684-016-0027-1.

33. Wiedenmann R., Zaeh M.F. Laser-assisted milling – Process modeling and experimental validation. *CIRP Journal of Manufacturing Science and Technology*, 2015, vol. 8, pp. 70–77. DOI: 10.1016/j.cirpj.2014.08.003.

34. Rakic S., Marjanovic U., Medic N. Advancements in smart manufacturing and Industry 4.0. *Applied Sciences*, 2025, vol. 15 (22), p. 11903. DOI: 10.3390/app152211903.

35. Lattanzi L., Raffaeli R., Peruzzini M., Pellicciari M. Digital twin for smart manufacturing: a review of concepts towards a practical industrial implementation. *International Journal of Computer Integrated Manufacturing*, 2021, vol. 34 (6), pp. 567–597. DOI: 10.1080/0951192X.2021.1911003.

36. Brecher C., Esser M., Witt S. Interaction of manufacturing process and machine tool. *CIRP Annals*, 2009, vol. 58 (2), pp. 588–607. DOI: 10.1016/j.cirp.2009.09.005.

37. Grzesik W. Hybrid additive and subtractive manufacturing processes and systems: A review. *Journal of Machine Engineering*, 2018, vol. 18, pp. 5–24. DOI: 10.5604/01.3001.0012.7629.

38. Lauwers B., Klocke F., Klink A., Tekkaya A.E., Neugebauer R., McIntosh D. Hybrid processes in manufacturing. *CIRP Annals*, 2014, vol. 63 (2), pp. 561–583. DOI: 10.1016/j.cirp.2014.05.003.

39. Wei C., Zhang Z., Cheng D., Sun Z., Zhu M., Li L. An overview of laser-based multiple metallic material additive manufacturing: from macro- to micro-scales. *International Journal of Extreme Manufacturing*, 2021, vol. 3 (1), p. 012003. DOI: 10.1088/2631-7990/abce04.

40. Koloskova A.V., Kiselev I.A., Ivanov I.I. Modelirovanie dinamiki protsessa tocheniya s uchetom podatlivosti obrabatyvaemoi detali [Modeling of the turning process dynamics, taking into the account the compliance of the workpiece]. *Internet-zhurnal «Naukovedenie» = Online Journal «Naukovedenie»*, 2017, vol. 9, no. 2, p. 70.

41. Ning H., Zhigang W., Chengyu J., Bing Z. Finite element method analysis and control stratagem for machining deformation of thin-walled components. *Journal of Materials Processing Technology*, 2003, vol. 139 (1–3), pp. 332–336. DOI: 10.1016/S0924-0136(03)00550-8.

42. Bolotein A.N. *Raschetnoe opredelenie tekhnologicheskikh ostatochnykh napryazhenii na osnove konechno-elementnoi modeli protsessa rezaniya*. Diss. kand. tekhn. nauk [Computational determination of technological residual stresses based on a finite element model of the cutting process. PhD eng. sci. diss.]. Rybinsk, 2014. 183 p.

43. Bao Y., Wang B., He Z., Kang R., Guo J. Recent progress in flexible supporting technology for aerospace thin-walled parts: A review. *Chinese Journal of Aeronautics*, 2022, vol. 35 (3), pp. 10–26. DOI: 10.1016/j.cja.2021.01.026.

44. Jiang X., Sun N., Ren F., Liu X., Guo W., Guo M., Fan X., Zhou J. Multi-process aerospace components: Residual stress modeling and deformation optimization. *International Journal of Mechanical Sciences*, 2026, vol. 309, p. 111077. DOI: 10.1016/j.ijmecsci.2025.111077.

45. Nosirov I.S., Belov A.M. Optimizatsiya parametrov protsessa rezaniya tokarnogo stanka s ChPU s ispol'zovaniem geneticheskogo algoritma [Optimization of parameters of a cnc lathe cutting process using a genetic algorithm]. *Izvestiya SPbGETU LETI = Proceedings of Saint Petersburg Electrotechnical University «LETI»*, 2020, no. 2, pp. 73–78.

46. You Q., Tang B. Efficient task offloading using particle swarm optimization algorithm in edge computing for industrial internet of things. *Journal of Cloud Computing*, 2021, vol. 10 (1), p. 41. DOI: 10.1186/s13677-021-00256-4.

47. D'Addona D.M., Teti R. Genetic algorithm-based optimization of cutting parameters in turning processes. *Procedia CIRP*, 2013, vol. 7, pp. 323–328. DOI: 10.1016/j.procir.2013.05.055.

48. Gavryushin S.S., Zhargalova A.D., Zaretskaya V.D. [Optimization of milling process calculations for thin-walled waffle-type parts using a genetic algorithm]. *Dinamicheskie i tekhnologicheskie problemy mekhaniki konstruktsii i sploshnykh sred* [XXVIII International Symposium «Dynamic and technological problems of a mechanics of constructions and continuous mediums» Dedicated to A.G. Gorshkov]. Kremyonki, 2022, pp. 64–65. (In Russian).

49. Martín-Mateos F.J., González Valencia L.C., Serrano Bello R. Expert system to real time control of machining processes. *Current Topics in Artificial Intelligence. CAEPIA 2009. Lecture Notes in Computer Science*. Vol. 5988. Berlin, Heidelberg, Springer, 2010, pp. 281–290. DOI: 10.1007/978-3-642-14264-2_29.

50. Wang Z., Liu S., Li H., Peng D., Cao H. A novel milling force prediction method based on the AI-empowered dynamic coupling model. *Mechanical Systems and Signal Processing*, 2025, vol. 241, p. 113497. DOI: 10.1016/j.ymssp.2025.113497.

51. Wang J., Ma Y., Zhang L., Gao R.X., Wu D. Deep learning for smart manufacturing: Methods and applications. *Journal of Manufacturing Systems*, 2018, vol. 48, pp. 144–156. DOI: 10.1016/j.jmsy.2018.01.003.

52. Eremeikin P.A., Zhargalova A.D. Avtomatizatsiya vybora ratsional'nykh rezhimov tokarnoi obrabotki tonkostennykh detalei [Automation of assignment of rational thin-walled parts turning mode]. *Inzhenernyi zhurnal: nauka i innovatsii = Engineering Journal: Science and Innovation*, 2017, no. 2, p. 4. DOI: 10.18698/2308-6033-2017-2-1587.

53. Zhargalova A.D., Gavriushin S.S., Lazarenko G.P., Semisalov V.I. O «myagkikh» rezhimakh rezaniya dlya obrabotki tonkostennykh detalei [About soft modes of cutting for processing thin-walled parts]. *Internet-zhurnal «Naukovedenie» = Online Journal «Naukovedenie»*, 2016, vol. 8, no. 6, p. 117.

54. Zaitsev V.M., Lepilin V.I. *Raschet naivygodneishego rezhima rezaniya pri tokarnoi obrabotke* [Calculation of the most advantageous cutting mode in turning operations]. Kuibyshev, Kuibyshev Aviation Institute Publ., 1974. 120 p.

55. Trembach E.N., Melent'ev G.A., Skhirtladze A.G. *Rezanie materialov: uchebnik dlya vuzov* [Material cutting]. Staryi Oskol, TNT Publ., 2012. 511 p. ISBN 978-5-94178-135-5.

56. Eremeykin P.A., Zhargalova A.D., Gavriushin S.S. Raschetno-eksperimental'naya otsenka tekhnologicheskikh deformatsii pri "myagkikh" rezhimakh tokarnoi obrabotki tonkostennykh detalei [Empirical evaluation of technological deformations for "soft" cutting modes during thin-walled parts turning]. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2018, vol. 20, no. 1, pp. 22–32. DOI: 10.17212/1994-6309-2018-20.1-22-32.

57. Wang L., Zhao H. A short review on machining deformation control of aero-engine thin-walled casings. *The International Journal of Advanced Manufacturing Technology*, 2022, vol. 121 (9–10), pp. 2971–2985. DOI: 10.1007/s00170-022-10587-9.

58. Wang Y.F., Wong Y.S., Fuh J.Y.H. Off-line modelling and planning of optimal clamping forces for an intelligent fixturing system. *International Journal of Machine Tools and Manufacture*, 1999, vol. 39 (2), pp. 253–271. DOI: 10.1016/S0890-6955(98)00026-1.

59. Liu H., Wang C., Li T., Bo Q., Liu K., Wang Y. Fixturing technology and system for thin-walled parts machining: a review. *Frontiers of Mechanical Engineering*, 2022, vol. 17 (4), p. 55. DOI: 10.1007/s11465-022-0711-5.

60. Zaretskaya V.D. Algoritm rascheta myagkikh rezhimov frezernoi obrabotki tonkostennykh detalei [Computation algorithm for soft modes of milling thin-walled parts]. *Politekhnicheskii molodezhnyi zhurnal = Polytechnic Youth Journal*, 2021, no. 7 (60). DOI: 10.18698/2541-8009-2021-7-715.

61. Raoufi K., Sutherland J.W., Zhao F., Clarens A.F., Rickli J.L., Fan Z., Huang H., Wang Y., Lee W.J., Mathur N., Triebe M.J., Desabathina S.S., Haapala K.R. Current state and emerging trends in advanced manufacturing: process technologies. *The International Journal of Advanced Manufacturing Technology*, 2024, vol. 135, pp. 4089–4118. DOI: 10.1007/s00170-024-14782-3.

62. Altintas Y., Kersting P., Biermann D., Budak E., Denkena B., Lazoglu I. Virtual process systems for part machining operations. *CIRP Annals*, 2014, vol. 63 (2), pp. 585–605. DOI: 10.1016/j.cirp.2014.05.007.

63. Zhou W., Yu F., Zhang J., Huang K., Xu Z., Liu X., Ma Y., Feng P., Feng F. An adaptive clamp system for deformation control of aerospace thin-walled parts. *Journal of Manufacturing Processes*, 2023, vol. 107, pp. 115–125. DOI: 10.1016/j.jmapro.2023.10.040.

64. Mal'tsev V.G., Morgunov A.P., Morozova N.S., Artyukh R.L. *Tekhnologicheskaya osnastka* [Technological equipment]. Omsk, OmSTU Publ., 2019. 134 p. ISBN 978-5-8149-2951-8.

65. Li W., Ren J., Shi K., Lu Y., Zhou J. Prediction of cutting force considering the influence of elastic deformation in ball end milling of thin-walled parts. *The International Journal of Advanced Manufacturing Technology*, 2025, vol. 140, pp. 4389–4403. DOI: 10.1007/s00170-025-16557-w.

66. Kurata Y., Merdol S.D., Altintas Y., Suzuki N., Shamoto E. Chatter stability in turning and milling with in process identified process damping. *Journal of Advanced Mechanical Design, Systems and Manufacturing*, 2010, vol. 4 (6), pp. 1107–1118. DOI: 10.1299/jamdsm.4.1107.

67. Li Z., Zeng Z., Yang Y., Ouyang Z., Ding P., Sun J., Zhu S. Research progress in machining technology of aerospace thin-walled components. *Journal of Manufacturing Processes*, 2024, vol. 119, pp. 463–482. DOI: 10.1016/j.jmapro.2024.03.111.

68. Bi Z.M., Zhang W.J. Flexible fixture design and automation: Review, issues and future directions. *International Journal of Production Research*, 2001, vol. 39 (13), pp. 2867–2894. DOI: 10.1080/00207540110054579.

69. Kritzinger W., Karner M., Traar G., Henjes J., Sihn W. Digital Twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine*, 2018, vol. 51 (11), pp. 1016–1022. DOI: 10.1016/j.ifacol.2018.08.474.

70. Filho P.T.J.C., Junior O.C. Digital Twin in Industry 4.0: Systematic review and content analysis and an architectural reference model. *Procedia Computer Science*, 2025, vol. 253, pp. 2919–2928. DOI: 10.1016/j.procs.2025.02.016.

71. da Silva L.R.R., Pimenov D.Y., da Silva R.B., Ercetin A., Giasin K. Review of applications of Digital Twins and Industry 4.0 for machining. *Journal of Manufacturing and Materials Processing*, 2025, vol. 9 (7), p. 211. DOI: 10.3390/jmmp9070211.

Conflicts of Interest

The authors declare no conflict of interest.