Побудов но тривимірні твердотільні моделі інструмент льних м г зинів дискового типу (н 14 інструментів) і л нцюгового типу н 32 інструмент , змонтов них н бічній поверхні стійки верст т . З пропонов но 3D-модель втоопер тор з гідроциліндром, що ре лізує втом тичну зміну інструменту. Сформов ний комплект моделей технологічного осн щення спільно з моделями інструмент льних м г зинів і втоопер тором д є цілісне уявлення про скл дність і особливості конструкторсько-технологічної підготовки процесів обробки н обробних центр х III і IV типорозмірів. Розроблено моделі т лгоритми п р метричного моделюв ння б зових елементів профільного різ льного інструменту. Використ ння вбудов ного п р метріз тор в модулі APM Graph дозволяє ре лізув ти більш простий підхід до створення моделей уніфіков них профілів інструменту, що прискорюють процес створення специ лізов них прикл дних бібліотек. Сформов но н літичні моделі для визн чення жорсткості формотворчих вузлів верст ті. Т кий підхід н йбільш ефективний для типових схем двохопорних шпинделів, з безпечених різном нітним інструмент льним осн щенням. Н против гу з г льноприйнятій процедурі, з пропонов ні н літичні моделі (ст тичні формуляри), що з безпечують отрим ння експрес-оцінок оптим льного співвідношення конструкторських п р метрів шпиндельних вузлів.

Т кий підхід до дослідження виклик ний тенденцією розширення технологічних можливостей обробних центрів, осн щених постійно змінною номенкл турою технологічної осн стки, що вдоскон люється. Появ нових видів допоміжного т різ льного інструменту повинно бути підкріплено метод ми і лгоритм ми, що зв'язують ет пи створення моделей конструкцій т оцінки їх пр цезд тності з критерієм жорсткості.

В умов х верст тобудівної г лузі, з пропонов ний в д ній роботі інструмент рій спрямов ний н підвищенні якості створення тривимірних моделей конструкцій, їх фоторе лістичного зобр ження, швидку д пт цію до умов, що змінюються, і опер тивну оцінку жорсткості формотворчих вузлів. Ре ліз ція з пропонов ного інструмент рію орієнтов н н підвищення конкурентоспроможності проектів, що розробляються

Ключові слов : 3D-моделюв ння, технологічне осн щення, п р метриз ція, рендеринг, інструмент льний м г зин, допоміжний інструмент, жорсткість

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DEVELOPMENT OF MODELS AND RESEARCH INTO TOOLING FOR MACHINING CENTERS

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1. Introduction

Effectiveness of the implementation of machining centers (MC) and multi-operational CNC machines is largely related to the development of a tooling system on a modular basis.

Modern machine-cutting tools and systems represent complicated assembly structures that include tool storage, tool positioners, auxiliary and cutting tools, which collectively form a tool system (TS). The practice of machine engineering has categorized tooling systems, in particular for CNC machines of drilling-boring and milling groups with the introduction of the concept of an instrumental module [1–3]. This module's housing includes various mounted instrumental units that render technological flexibility to TS.

The downside of technological flexibility is the complexity of defining basic characteristics of strength, rigidity and vibration resistance within the boundaries of a machine's working zone. Of particular importance is the factor of rigidity of the forming node spindle-tooling unit, which predetermines the accuracy of machining that is the limiting factor for the technology of manufacturing at MC. A change in the tool outreach length during cutting makes these characteristics variable. Hence the need to control quantitative values and to compare them with the permissible values. Research into TS implies creating a database of 3D models of tool storage, auxiliary, cutting tools and tool units in general. The specificity of the objects considered – unification, a large nomenclature of different types of tooling, makes it effective to use a technology of parametrization when constructing the models of structures. The availability of 3D modeling with a principle of associativity makes it possible to generate any required outlays and cross-cuts, that is, to form basic drawings, obtain initial data for calculations and related tasks. And, most importantly, a correctly constructed model makes it possible to obtain absolutely accurate lists of equipment, products and materials used in a given model – specifications, bills of materials. In order to implement a 3D modeling of the tooling system it is advisable to use the rapidly advancing system KOMPAS-3D that employs a technology of integrated end-to-end 3D design and rendering, developed by ASCON group of companies [4, 5].

However, it is necessary to associate the 3D modeling systems of tooling with the estimation modules of design assessment for durability, vibration resistance, and in particular rigidity, which has the greatest influence on the accuracy and quality of the resulting products. This is especially important for modern machine complexes intended for the finishing and precision machining of high-precision parts. The share of such machines in the fleet of machine-building enterprises increases, which indicates the relevance of rigidity evaluation methods. Such a situation from the methodological point of view necessitates parallel use of 3D modeling tools with parameterization and application of research methods related to the rigidity of shape-forming machine nodes and its instrumentation.

2. Literature review and problem statement

Growing level of design complexity in the tool-making industry, creation of competitive structures imply the extensive use of various computer aided design systems. For the technology of design process, of growing importance are the procedures for building 3D models and parametric representation of parts and assembly units.

Paper [6] shows the efficiency of applying a solid machine model for the tasks on control over a machining process. This approach, as an alternative to control methods based on the cyclograms of tool movement, was used for five-coordinate machines and machining centers. But the issues of compiling (applying) the set of auxiliary and cutting tools for different technological processes were not emphasized. When describing the user interface of the control program, the author refers to a library of models for the generalized 5-axis machine configurations. This library lacks a separate section of 3D models technological tooling, including tool storage, tool positioners, and instrumental units. The need for such an tool section in the user libraries for machining centers is predetermined by the tendency of expanding technological capabilities of machines through the use of a large number of designs for technological equipment.

Paper [7] considered machinability of product within a life cycle of a triaxial milling machine equipped with instrumental tooling of the Bridgeport DIN 69871 type. The author applies a systems approach to evaluation the effectiveness of machining taking into consideration the interaction between basic forming machine nodes: a feed drive, a spindle node, and a tooling system. They use, as auxiliary tools, the mandrels in line with the standard ISO 230 series, which correspond to the tooling of small-sized machines (standard sizes one and two). Hence the libraries of 3D models are focused on the limited scope of application. Thus, the tooling system of the considered machine has a disk tool storage for 14 tool items. To machine more complex housing parts, chain tool storage are applied that are equipped with a significantly larger number of instruments. The enhanced sizes of housing parts require milling and multi-functional machines of standards sizes III and IV with a tooling in line with the standards ISO 40 and ISO 50. There is a problem related to the implementation of the approach proposed by the author for the machines of other standard sizes, and therefore the construction of appropriate sets of 3D models of tool storage and their tooling.

In the modern systems for automated design of the «medium» and «heavy» classes the availability of a parametric model is rooted in the ideology of CAD themselves. The existence of an object parametric description is the base for the entire design process. Almost all systems, such as Autodesk Mechanical Desktop, Unigraphics, CATIA, I-DEAS, etc., employ the same parametrizer by the English company D-CUBED.

Such a widespread system as KOMPAS-3D CAD is equipped with a proprietary system of parametric modeling, including geometric and parametric core, as well as data-sharing and visualization modules [8]. This system is being constantly improved by adding new design functionals. Thus, the geometric core C3D Modeler builds a geometric model and calculates geometrical characteristics of the modeled object. The latest variant of C3D Modeler is equipped with the functionality that makes it possible to remove hole and roundings from a model. It is aimed at simplifying a 3D model, which is prepared for subsequent calculation in a computer-aided engineering system (CAE-system).

Designs of tool units are characterized by rather complicated spatial curves with rounding. The geometric core of C3D Modeler has a modified construction of rounding that absorbs elements of the original 3D model. The system now operates with a previously unavailable combinations of rounding, which can be used in applications for both designing the housing parts of TU with a different configuration and for tools with a complex shape.

The year of 2018 will see a new generation of parametric modeling technologies «Parametric modeling 2.0», based on the programming environment Onshape, which would improve the features from the previous generation for several key areas [9]. These include: a simultaneous simulation of multiple components, configurations, and other directions.

While modeling simultaneously the auxiliary and cutting tools, it is effective to use a single parametric operation tree, enabled by the parameterization 2.0. The built-in Onshape capabilities expanded the possibilities for parametric modeling from one part to a multitude of interrelated elements that are used independently of each other in assemblies, specifications, and applications [9]. Thus, there is now a possibility to drill a hole through the flanged junction of an tool unit and a spindle. Similarly performed is the rounding for all edges of a given pair of nodes, which can be done in one operation.

An integrated design of tooling equipment access to the following modules:

– keeping of standard parts and assemblies, as well as reference data from machine-building industry;

– keeping of graphical information on standard parts and nodes;

– keeping of standard information data for designing technological processes.

Such a possibility can be provided by the integrated APM WinMachine CAD [10], which includes the APM GRAPH module. This module's special feature is a built-in parametrizer that provides for an improvement in performance, on the one hand, and better quality of design solutions on the other hand. In this system, the constructive graphical elements in the form of parametric objects in the APM GRAPH environment are included in the databases of the APM Mechanical Data, APM Construction, and APM Technological Data. These parametric objects act as base elements to automatically generate drawings in engineering modules.

Paper [11] devoted to the development of a metal-cutting tools design technique using parametric 3D modeling. The authors create a parametric prototype for each type of a cutting tool with similar image fragments that differ only in size.

The proposed design technique is based on the procedure of successive construction of a 3D model using the variables that reflect relationship between different graphical objects. These relationships are the assigned angles and distances between the planes of cutting part of the tool surface and the sketching planes of the model that is being built. In the KOMPAS-3D CAD the specified relations are determined by assigning the dimensions using an option for parameterization. The examined object was a boring cutter. For the case of a milling tool with a complex shape, description of the relationship between graphical objects is not limited to angles and distances. Thus, a set of 8 cutters is applied for disk gear cutters with a module to 8 mm, designed for cutting wheels with a certain number of teeth. For mills No. 1–5 a tooth contour is shaped by a profile of type I, consisting of the circle arc, a straight line, and an involute curve. The profile of type II is characterized by a different combination – a line segment, an arc, and an involute curve (mills No. 6–8). This complicates the procedure of parametric descriptions owing to the introduction of variables such as a number of the cutter, a profile type, etc.

The performance of tooling in machining centers is studied based on the criterion of rigidity, which directly affects the accuracy of machining.

Paper [12] addresses the influence of rigidity and geometrical parameters of a spindle node (SN) equipped with a boring bar on the accuracy of a hole boring operation. The authors derived an analytical equation of SN deflection on the elastic deformations of a spindle and it supports, as well as a pinched moment in the front support. They point to the diversity of designs of boring machines and their tooling at the unification of a spindle node but fail to consider the issue of influence of the tool unit (boring bar – boring cutter) on the total rigidity of the main shape-forming node of the machine.

Work [13] addresses the influence of rigidity of shape-forming nodes in a CNC drilling-boring and milling machine on the machining error [13]. A new approach is proposed that relates to modeling a field of static rigidity using the main parameter – «generalized rigidity» – at the scale of the machine working area. The advantage of a given work is the construction of a parametric model in a 6-coordinate machining space, which enables the assessment and prediction of possible machining errors. At the same time, the work misses the features of change in tooling and its parametric representation. A similar approach is also employed in paper [14] while not applying the developed 3D modeling and parameterization.

Analysis of the current state of developments in the field of designing machining centers for machine-building industry has revealed the relevance of the task on providing the tools for machine equipment. In order to expand the technological capabilities of such equipment, there is a need to construct new sets of 3D models of disk tool storage and chain types for machines of standard sizes III and IV. These tool storage require the construction of separate sections of three-dimensional models for auxiliary and cutting tools using a rendering technology. For tools with a complex profile with standardized elements of mounting and cutting parts, it is advisable to apply specialized parameterization programs similar to the APM Graph module. Efficient research into tooling performance is associated with the development of such analytical models of a machine's shape-forming nodes that would make it possible to estimate characteristics of rigidity when implementing various technological machining operations for machine-building product.

3. The aim and objectives of the study

The aim of present work is to improve efficiency of the tooling design process for equipment of the machining center type by performing solid modeling and constructing parametric models of the auxiliary unified elements and cutting tools.

To accomplish the aim, the following tasks have been set:

– to construct the sets of solid models for basic components of the machining centers tooling system – tool storage, tool positioners, auxiliary and cutting tools;

– to build parametric models of unified elements for cutting tools of complex shape in the APM Graph module;

– to investigate and estimate rigidity of tool blocks for shape-forming nodes and to determine the optimal ratio of their limiting sizes.

4. Materials and research methods

Let us consider a process of research into an tooling system of a drilling-milling-boring machining center. The central element of such a system is the tool storage. Selection of the type of a tool storage is determined based on the purpose, type and layout of a multi-operational machine. An analysis of the diversity of medium size housing parts, which are expedient to machine at multi-operational machines, reveals that the most applied are the tool storage that contain up to 40 tools, mainly the disk or chain ones.

Specialized machining centers apply an automated tool changer (ATC) with a disk tool storage, mounted at the machine upright, and a two-grip manipulator (Fig. 1). Such storage are used to hold a small number of tools (no more than 18 provided the tools are arranged in one row) and are characterized by the simplicity of design and small dimensions. A tool change is performed at the fixed position of a spindle head.

To study the properties of an tooling system of the machining center based on model SVM1MF4, we constructed three-dimensional models of ATC device of the disk type [5, 15, 16], which contain 1,330 3D models of parts and assemblies, shown in Fig. 1, 2.

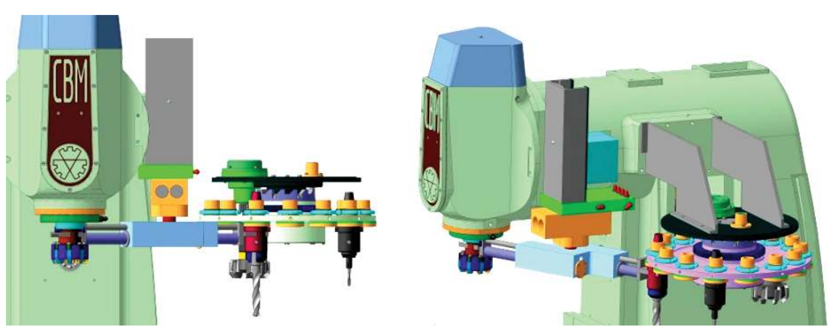


Fig. 1. Design of an automated tool changer

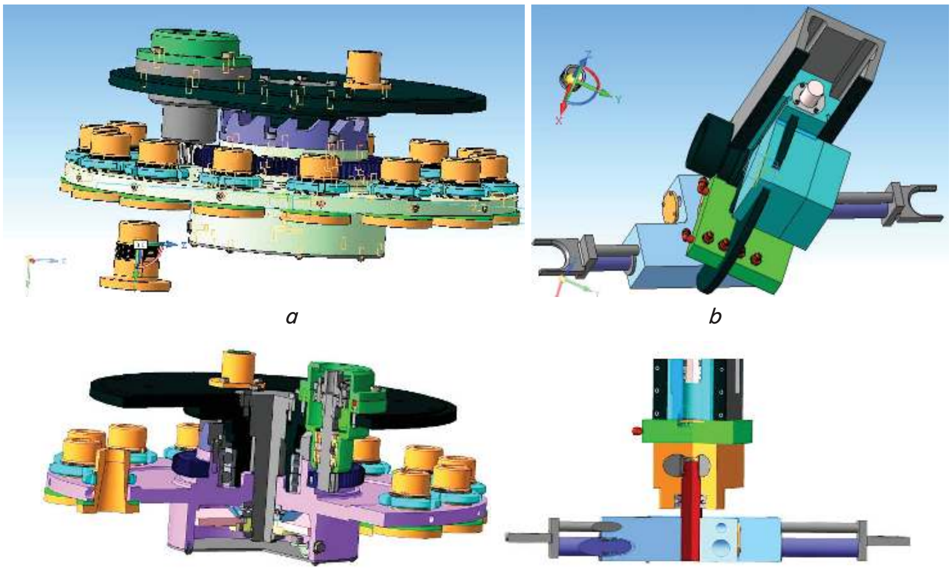


Fig. 2. 3D model of disk tool storage and tool positioners:
a — disc tool storage for 14 tool holders; *b* — tool positioner; *c* — tool storage cross-section;
d — tool positioners cross-section

For complex housing parts whose machining requires a large number of technological operations, chain tool storage with large capacity have been utilized. In this case, a storage is mounted on the side of the upright while tool positioners perform a rotation around the vertical axis. For a given variant of TS there are proposed 3D models of a chain tool storage for 32 tool holders (Fig. 3).

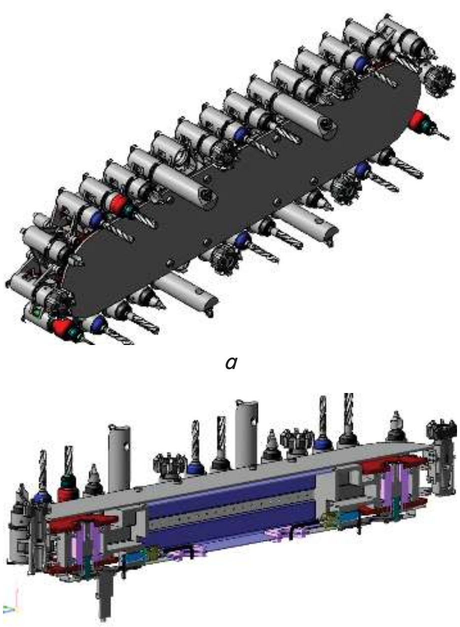


Fig. 3. 3D model of a chain tool storage:
a — general layout; *b* — cross-section

Machine tool systems are equipped with tooling units, which include a specific set of auxiliarity tools used to mount and install cutting tools of various designs. In this paper we implemented a procedure for constructing 3D models of tool units [16] in the system KOMPAS-3D: for milling (Fig. 4, *a*, *b*), drilling (Fig. 4, *c*), reaming (Fig. 4, *d*), and others.

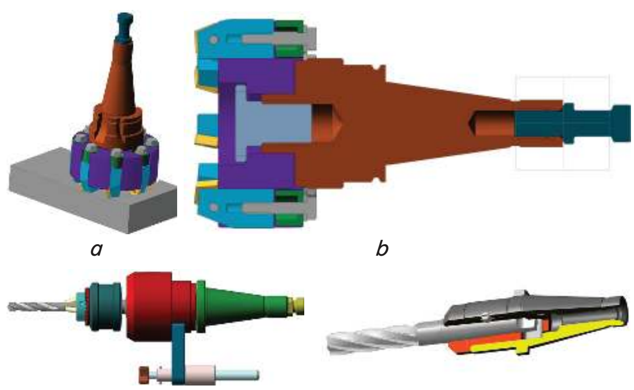
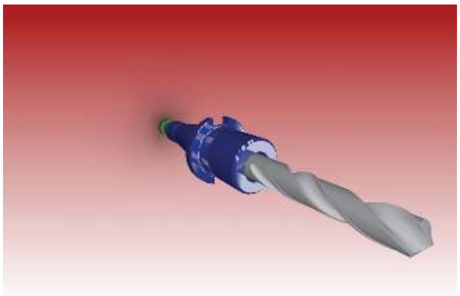


Fig. 4. Tool units of machining centers:
a, *b* — face mill; *c* — speed drilling head; *d* — mandrel for reaming

We use the means of the CAD KOMPAS-3D to create a photorealistic image of the tooling using a drilling operation as an example (Fig. 5, *a*), as well as a milling operation using an angular head (Fig. 5, *b*). To this end, we apply the built-in module Artisan Rendering whose advantages include the simplicity and speed of producing a complete snapshot, as well as a possibility to view and generate multiple snapshots for programming rendering. The module utilizes a combination of high-quality hardware OpenGL rendering for installation and viewing, along with rendering for ray tracing from high quality images and global illumination. The module includes tools for the combination of materials and lighting, textures, and relief patterns. At the same time, the textures contain reflections and transparency of such elements as mirror or glass.

Applying this module enables the formation of an accurate image of the designed object's physical appearance, prior to the emergence of a designed product. Fig. 6 shows the rendering image of a six-spindle turret head in the Artisan Rendering module.



a

b

Fig. 5. Rendering of tooling: *a* — for drilling; *b* — for milling

An even more efficient tool for improving a designer's productivity is to use a parametric modeling apparatus in the practice of research and design of tools with a complex shape. The varied nomenclature of tools for machining a wide range of engineering products on the one hand and the availability of unified structural elements on the other hand makes it a relevant task to construct parametric models of tools with a complex shape. The actual process of design is characterized by the fact that the final values for a part size are typically unknown in advance and are subject to additional refinement. Hence the need to edit parametric dimensions.

The integrated APM WinMachine CAD [17, 18] includes the APM GRAPH module that enables efficient construction of generalized parametric projects. These projects can subsequently assist to implement in the shortest time a procedure of multivariate design and to construct any tool variant.

A special feature of the APM GRAPH module is a built-in parametrizer providing an improvement in performance, on the one hand, and improving the quality of design solutions on the other hand. A parametric model is a sequence of drawing orders with the specified parameters. Parameters are specified either numerically or through mathematical expressions. The algorithm for a parametric model construction and the syntax of the CAD APM WinMachine are given in [19].

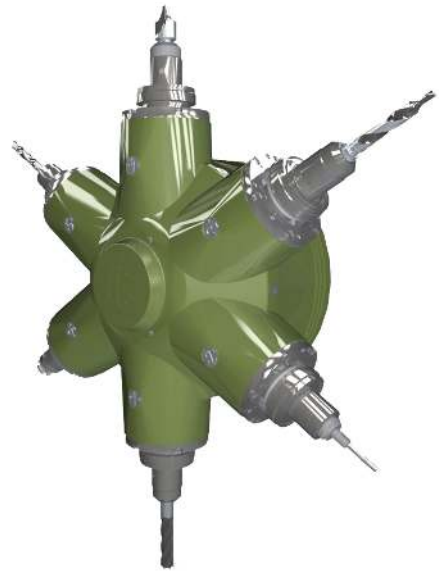
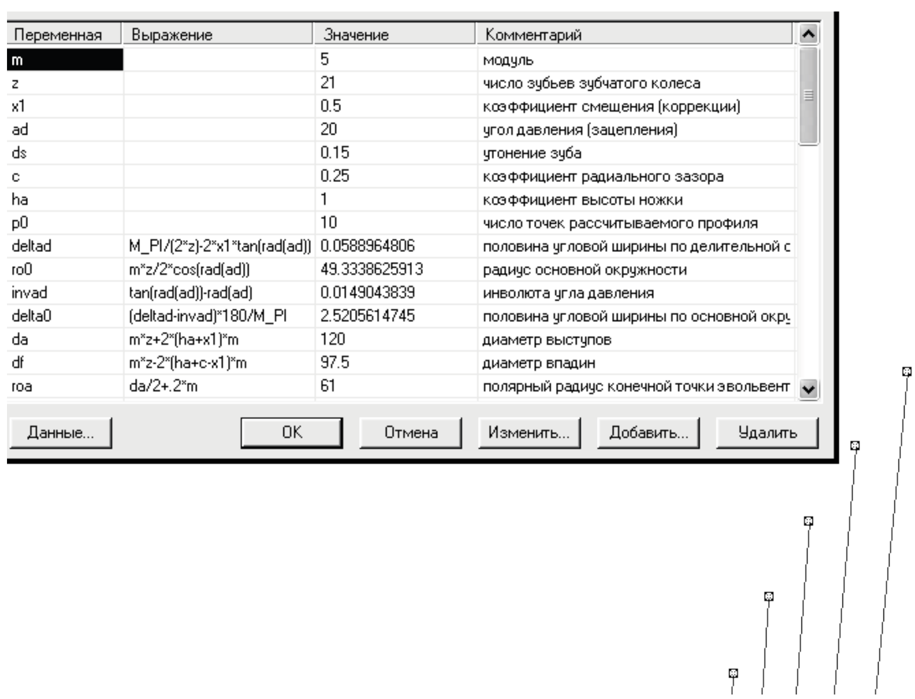


Fig. 6. Rendering of a six-spindle turret head

A limiting operation for machining centers of the drilling-milling-boring type is the milling operation using cutters whose working part might include both an involute profile and non-involute profile.

For a wide range of such tools the APM Graph module [19, 20] employs the built parametric model of the involute profile of a cutter's tooth cutting part (Fig. 7) using analytical ratios shown in the variables window [18].

Along with a sharpened tool that works by the method of copying, there is a large nomenclature of cutters with a form-relieved tooth rear surface operated based on a generating method.



Переменная	Выражение	Значение	Комментарий
m		5	модуль
z		21	число зубьев зубчатого колеса
x1		0.5	коэффициент смещения (коррекции)
ad		20	угол давления (зацепления)
ds		0.15	утонение зуба
c		0.25	коэффициент радиального зазора
ha		1	коэффициент высоты ножки
p0		10	число точек рассчитываемого профиля
deltad	M_PI/(2*z)-2*x1*tan(rad(ad))	0.0588964806	половина угловой ширины по делительной с
ro0	m*z/2*cos(rad(ad))	49.3338625913	радиус основной окружности
invad	tan(rad(ad))-rad(ad)	0.0149043839	инволюта угла давления
delta0	(deltad-invad)*180/M_PI	2.5205614745	половина угловой ширины по основной окру
da	m*z+2*(ha+x1)*m	120	диаметр выступов
df	m*z-2*(ha+c-x1)*m	97.5	диаметр впадин
roa	da/2+.2*m	61	полярный радиус конечной точки эвольвент

Fig. 7. Parameterization of the involute profile

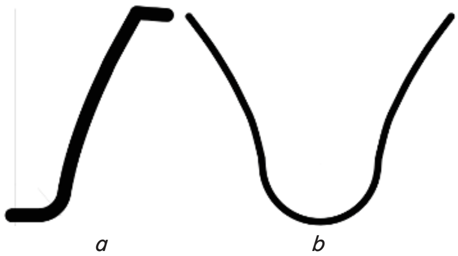


Fig. 8. A profile of the groove in a cut tooth gear: *a* — involute profile with a transition curve; *b* — contour of a tooth groove

The APM Graph module [17, 21] includes the constructed parametric models of one- and two-time form-relieved cutter surfaces outlined by the Archimedean spiral (the magnitude of the radius vector gain is directly proportional to the magnitude of the polar increment angle) [20]. Fig. 9 shows a window of parametric commands in the problem on constructing a one-time form-relieved tooth; Fig. 10 shows a sequence of graphical operations and the parameterized contours of a single-time and two-time form-relieved tooth of a cutter.

Upon constructing a parameterized form-relieved tooth contour using the drawing-graphical editor of the APM Graph, we build a sketch of a tooth cutting tool using the command «circular array». That makes it possible to apply parameterization means to a wide range of tools with a complex shape, thereby significantly improving the productivity of a tool designer.

The diversity of types of instrumental units and increased requirements to the quality of products necessitates conducting a research into evaluation of spindle nodes rigidity in machines equipped with various tooling.

The investigated object is a spindle node of a multi-operational machine for the drilling-milling-boring type, model SF68PF4. Estimation of a given node performance based on the criterion of rigidity will be carried out in the following sequence.

1. Construct a 3D model of a two-support spindle node in the 3D CAD environment (Fig. 11, *a*). A simplified structural 3D layout is shown in Fig. 11, *b*.

2. Construction of structural diagrams and determining the mounting layout. The spindle of a given machine is loaded with console force $P = 400$ N and is a hollow shaft ($d = 65$ mm; $d_0 = 28$ mm) with a standard end (flange type in line with GOST 12595-2003). A two-support spindle is mounted on dual combined duplexed angular contact ball bearings with a preliminary loading based on the scheme «tandem-O» (Fig. 11, *c*). The front support exploits bearings of an especially light series 2-446113 GOST 832-78 with a contact angle $\alpha = 26°$. The back support holds two combined duplexed angular contact ball bearings of an especially light series 2-446112 GOST 832-78. Another variant considered is the X-shaped diagram assembly (Fig. 11, *d*).

3. Development of a parametric model of the spindle. It is executed by a 2D graphical editor of the APM Graph module in the APM WinMachine [18, 19]. For standardized double-support spindles mounted on dual combined duplexed angular contact ball bearings with a conical seat hole of type 7:24 regulated by GOST 24644-81, there is a developed parameterization software. Fig. 12 shows a fragment of this software in a variables window of the APM Graph module.

4. Modeling a spindle node based on the criterion of rigidity.

We shall consider the displacement of a tooling unit (TU), which is mounted in the spindle, taking into consideration the deformation of its supports that can be represented in the form [22–25]:

$$y_2 = \frac{Pl_1^2 l}{3EJ_1} + \frac{Pl_1^3}{3EJ_2} = \frac{P}{j_0}\left(1 + \lambda \frac{J_2}{J_1}\right),$$

where P is the resultant force given to the cutting tool; l, l_1 is the inter-support distance and the tooling unit length; $\lambda = l/l_1$ is the indicator characterizing relative length of the passage of elastic link «Spindle–Tool unit» (S-TU); $j_0 = 3EJ_2/l_1^3$ is the conditional rigidity of console part of S-TU.

For spindles on the rolling bearings additional restrictions are assigned for the minimum distance between supports ($\lambda_{min} \geq 2.5$) due to the fact that the beating of bearings while further reduction in the inter-support distance increases the beating of a spindle end [26, 27].

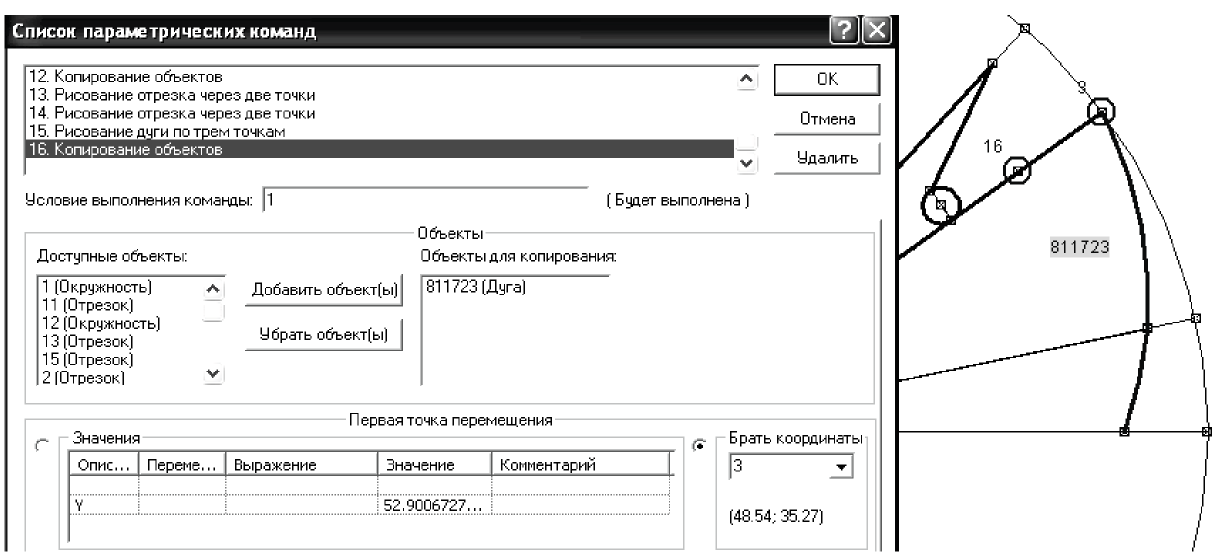
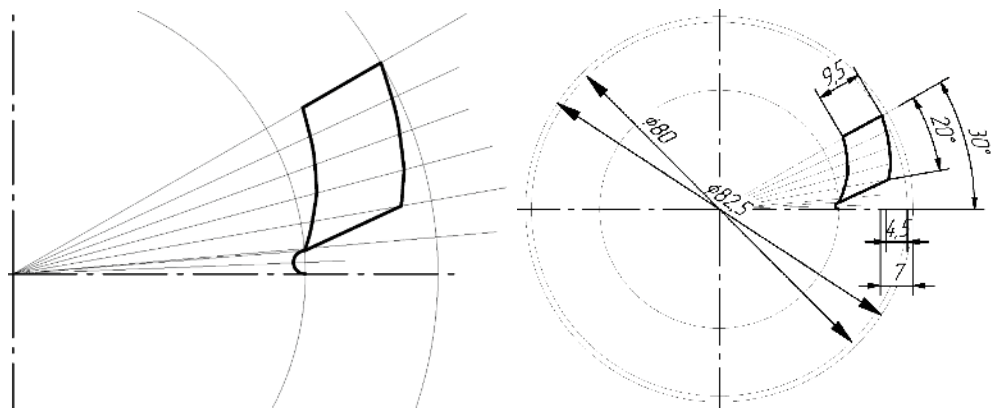
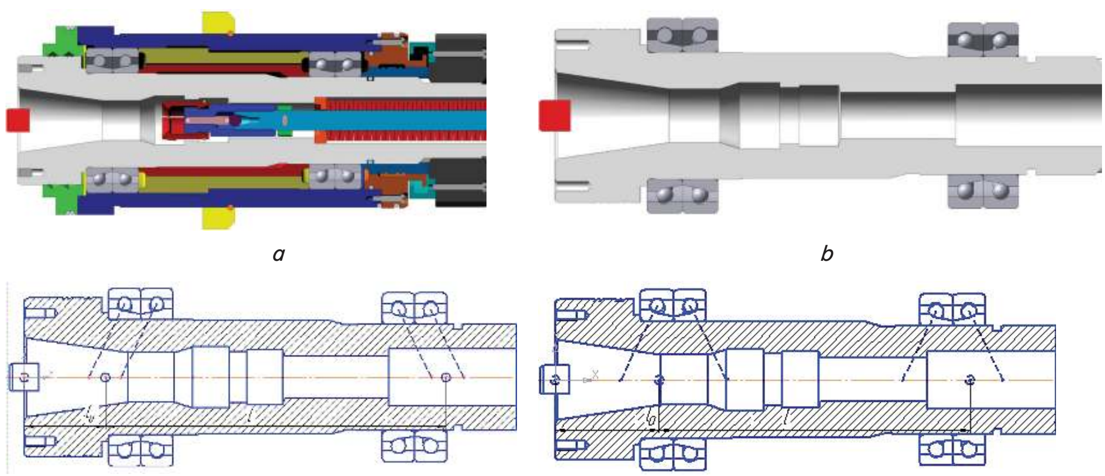


Fig. 9. Command window for the task on parameterization of the form-relieved tooth



a *b*

Fig. 10. Form-relieved tooth rear surface: *a* — one-time form relief; *b* — two-time form relief



a *b*

c *d*

Fig. 11. Spindle node rigidity calculation

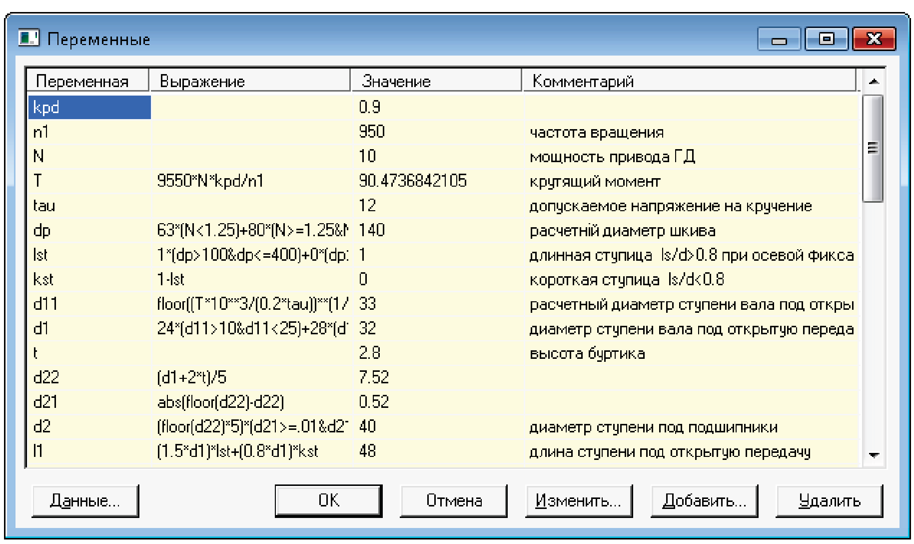


Fig. 12. Fragment of the spindle parametric simulation software

We shall consider a procedure for determining the optimal ratio of console lengths TU and inter-support part for a common model of multi-operational machines of the drilling-milling-boring type SF68PF4.

Elastic front and back supports are characterized by the respective characteristics of ductility: linear – $A_z = 3.99\cdot10^{-6}$ mm/N and $A_p = 3.93\cdot10^{-6}$, mm/N; angular – $a_p = 0.38\cdot10^{-8}$, 1/N·mm; $a_z = 0.48\cdot10^{-8}$, 1/N·mm.

Using a kernel of the symbolic mathematic from the system MAPLE, we shall define the displacement of the spindle end due to the deformation of its supports, which can be represented in the form:

$$y_1 = \frac{0.001668(\lambda+1)^2}{\lambda^2} + \frac{0.001668}{\lambda^2}.$$

Deflection of the spindle as an elastic beam can be represented in the form:

$$y_2 = 0.0008533 + 0.000547\lambda.$$

Overall spindle node ductility (static backlog), calculated for the console part, will equal:

$$\delta = \frac{0.001668(\lambda+1)^2}{\lambda^2} + \frac{0.001668}{\lambda^2} + 0.0008533 + 0.000547\lambda.$$

A graphical representation of the considered problem on finding the optimal ratio λ based on the components of support ductility y_1 of a spindle node and its console part y_2 is shown in Fig. 13.

The magnitude of the relative span length ($\lambda_{min} \geq 2.5$) is a constraint; a designer must take the optimal decision. In this case, the optimal ratio is $\lambda_{opt} = 3.12$. However, a designer often has to accept a technical compromise. It is therefore important, along with the exact value of the optimum, to provide for a range of values over which total ductility will be slightly exceeded [25, 26]. The result obtained makes it possible to compile a rational range of values for ratios between linear characteristics $2.7 \leq \lambda \leq 3.8$.

Let us consider the way the magnitude of a spindle displacement changes with an increase in the inter-support distance by employing the APM Shaft module of the CAD system from the APM WinMachine [28–30]. Using the APM Shaft module we constructed ductility diagrams for two variants of the relative span length (Fig. 14).

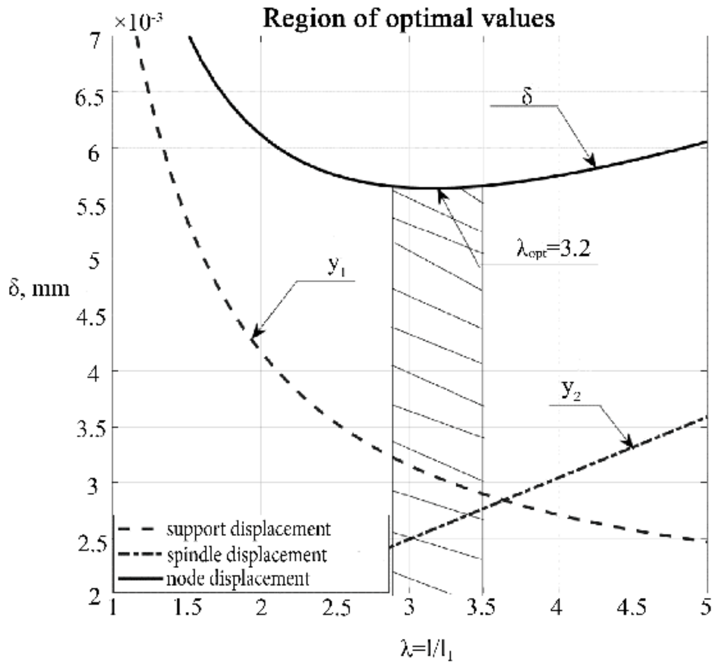
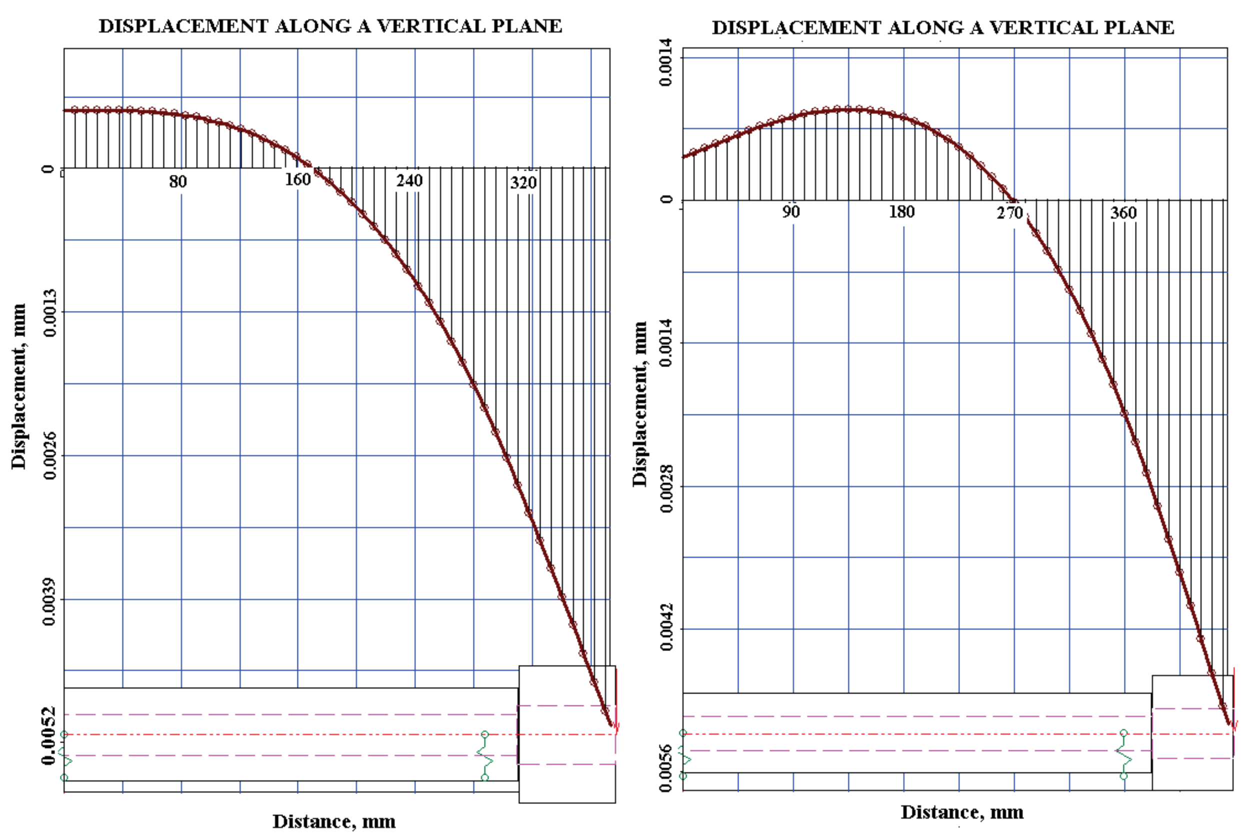


Fig. 13. Optimum ratio of the spindle sizes



a *b*

Fig. 14. Spindle ductility at various inter-support distances: *a* – shaft displacement at λ=3.2; *b* – shaft displacement at λ=4.0

Based on the diagrams derived, it is possible to draw a conclusion about an increase in the degree of deformation with an increase in the inter-support distance *l*. When λ increases by 20 % (from 3.2 to 4), the magnitude of a spindle displacement along a console increased by about 8 % (from 0.0052 to 0.0056 mm). At the same time, it should be noted that a decrease in the length of console part leads to an increase in the value for optimum ratio λ_{opt}. In these cases, the best strategy would be to increase the inter-support distance that may be restricted for design considerations. It is obvious that it is necessary to account for the angular ductility of a single bearing because the calculated value δ for a spindle node increases by 3.2 times. As shown by the calculation, a change in the linear ductility A_z and A_p of supports without a corresponding change in its diameter will not make significant changes to the ductility of a spindle node (it does not exceed 3.5 %).

5. Discussion of results of studying the tooling

A 3D modeling process makes a designer face a task on establishing a relation to the estimation modules, that is, there is a connection to the problem on examining the feasibility, for example, for the criterion of rigidity. This leads to the need of using, in parallel, 3D modeling tools with parameterization and research methods in the area of rigidity of shape-forming machine nodes and its tooling.

The process of constructing a 3D model should account for the types of finite elements applied in practice:

a) rod;

b) laminar;

c) volumetric.

The most common in tool units modeling tasks are the rod finite elements. For the sake of correctness of the problem being solved, one should define a condition for the unique fixation in space, on the one hand, and the presence of free nodes with permitted displacements (due to deformation under the influence of cutting forces), on the other hand. In the case of representing an auxiliary tool (mandrel) in the form of a beam on two hinged supports, which do not allow the displacement in the direction of an external force, such free nodes are missing. This leads to the need to introduce an additional free node at the early stages of 3D modeling, which permits displacements in the direction of the applied loads. Otherwise, the problem is not correct because when calculating using a method of finite elements, primarily determined are the displacements of nodes. Internal loads at nodes and stresses are calculated based on its displacements. Such a situation leads to a *feedback* (*type I*) between a stage of constructing a 3D model and the stage of investigating effectiveness of the design, for example, for the criterion of rigidity.

Along with the need to take into consideration the peculiarities of fixing and loading, determined at the stage of constructing calculation schemes of tool units, there is also another type of a feedback. Such a feedback is related to the methods for solving problems on the evaluation of rigidity. Thus, for tool units working at bending with an insignificant torque (for fine boring), it will suffice to use in strength calculation such known methods of materials resistance as a method of initial parameters. Otherwise, at a large share of torque (for face milling), a finite element method is employed. In this case, a tool unit's cross-section (in the form of a rod) is split into flat finite elements that interact through nodes. Such a situation leads to the emergence of a *feedback* (*type II*) between a stage of constructing a 3D model and the stage of selecting a method for the calculation of designed structure.

6. Conclusions

1. We have performed a comprehensive study into designs of a tooling system for machining centers of the drilling-milling-boring type using the integrated CAD KOMPAS and the APM WinMachine. That makes it possible not only to provide for a complete pattern of the design, but also take into consideration the peculiarities of functioning of metal-cutting equipment with different sets of tooling. The process of creating a new product often takes place under the «Digital Divide» mode when a designer analyzes a structure over a short period of time, constructing a 3D model, developing the tooling, and selecting appropriate cutting and auxiliary tools. Given the wide availability of machines of the machining center type, unified equipment and tools, the proposed 3D models of components for a tooling system using the applied KOMPAS-3D system libraries and a parameterization apparatus would improve the process of launching a new product. It was proven that a considerable amount of time during manufacturing is taken by a tool change procedure. In this regard, in order to utilize t he standardized designs of cutting tools, we have proposed the 3D solidmodels of a disk tool storage (for 14 tools) and a chain tool storage for 32 tools to machining centers of standard size III and IV. To create a photorealistic image of both a tools storage and an tool positioners and the sets of cutting tools, we applied the module Artisan integrated in the system KOMPAS-3D.

2. A constant change in the nomenclature of manufactured products is connected to the development of specialized tools with a complex shape. Promising are specialized applied libraries in the environment of integrated CAD systems. Such software includes the «Frez» CAD in the KOMPAS system. However, there are tools with a non-standard profile. To accelerate the work at the stage of constructing 3D models, we have built algorithms for the parameterization of unified contours of the milling tools' profile in the APM GRAPH module. We have constructed parametric models of the involute contour of a cutter tooth with a single and double form-relieved surface. This greatly accelerates the process of designing a cutting tool and the tooling, particularly under conditions of multi-variant design.

3. An important aspect for modeling procedures is the integrated research into performance of shape-forming spindle nodes, with the main criterion being rigidity. This problem is of a multifactor nature. We have proposed a 4-step procedure starting with the construction of three-dimensional models of spindle nodes. We have considered structural diagrams of double-support spindles with respect to the assembly techniques of combined duplexed angular contact ball bearings. Research has been conducted to ensure the rigidity of tool units mounted at the shape-forming spindle nodes of machining centers. Using the built static backlogs (symbolically) we perform an express calculation and determine the optimal ratio between the sizes of inter-support and console parts of the spindle, which ensures maximum rigidity of the tool unit.

The results obtained in this paper would make it possible to construct parametric models, drawings, and 3D models of the instrumental system components of different design implementations under the mode of a three-dimensional, parametrical, and analytical modeling.

References

1. Kuznetsov Yu. I., Maslov A. R., Baykov A. N. Osnastka dlya stankov s ChPU [Tooling for CNC machines]: spravochnik. Moscow: Machinostroenie, 1990. 510 p.
2. Metallorezhuschie stanki [Metal-cutting machine tools]. Vol. 1: uchebnik / Avraamova T. M., Bushuev V. V., Gilovoy L. Ya. et. al.; V. V. Bushuev (Ed.). Moscow: Machinostroenie, 2012. 608 p.
3. Grigorev S. N., Grechishnikov V. A., Maslov A. R. Instrumentalnyie sistemyi integrirovannyih mashinostroitelnyih proizvodstv [Instrumental systems of integrated machine-building productions]: monografiya. Moscow: FGBOU VPO MGTU «STANKIN», 2012. 194 p.
4. Ganin N. B. Trehmernoe proektirovanie v KOMPAS-3D [Three-dimensional design in KOMPAS-3D]. Moscow: DMK, 2012. 776 p.
5. Krol O. S. Metodyi i protseduryi 3D-modelirovaniya metallorezhuschih stankov i instrumentov [Methods and procedures of 3D modeling of metal-cutting machines and tools]: monografiya. Lugansk: Izd-vo VNU im. V. Dalya, 2015. 120 p.
6. Li J., Song Y., Liu Y. Development of post-processing system for three types of five-axis machine tools based on solid model // ASME 2017 12th International Manufacturing Science and Engineering Conference collocated with the JSME/ASME 2017 6th International Conference on Materials and Processing. 2017. P. 118–132. doi: 10.1115/msec2017-2665
7. Determination of Machinability Considering Degradation of Accuracy Over Machine Tool Life Cycle / Afsharizand B., Zhang X., Newman S. T., Nassehi A. // Procedia CIRP. 2014. Vol. 17. P. 760–765. doi: 10.1016/j.procir.2014.02.048
8. Kamnev A. C3D Labs predstavlyaet C3D Toolkit 2017. Aktualnyie tehnologii dlya razrabotchikov inzhenernogo PO [C3D Labs presents the C3D Toolkit 2017. Topical technologies for developers of engineering software] // SAPR i grafika. 2017. P. 42–47. URL: http://c3dlabs.com/source/documents/SiG_05-2017_C3D_Toolkit.pdf
9. Girschtick J. Introducing parametric modeling 2.0 // Isicad. 2018. URL: http://isicad.net/articles.php?article_num=19641
10. Krol O. S. Construction of parametric models of belt-drive using APM WINMACHINE // Eastern-European Journal of Enterprise Technologies. 2013. Vol. 2, Issue 7 (62). P. 61–63. URL: http://journals.uran.ua/eejet/article/view/12391/10279
11. Pritykin F. N., Shmulenkova E. E. Osnovnye elementy SAPR metallorezhushchih instrumentov pri ispol'zovanii parametricheskogo 3D modelirovaniya [Basic elements of CAD of metal-cutting tools using parametric 3D modeling] // Omskiy nauchniy vestnik. 2012. Issue 1 (107). P. 278–282.
12. Vliyanie zhestkosti i geometricheskih parametrov shpindel'nogo uzla pinoli na tochnost' rastachivaniya soosnyh otverstiy [Effect of rigidity and geometric parameters of the spindle pinol assembly on the accuracy of boring of coaxial holes] / Saninskiy V. A., Ryabova K. L., Platonov Yu. N., Osadchenko E. N. // Sovremennye problemy nauki i obrazovaniya. 2013. Issue 2. P. 15–21.
13. Stiffness modeling of machine tools based on machining space analysis / Gao X., Li B., Hong J., Guo J. // The International Journal of Advanced Manufacturing Technology. 2016. Vol. 86, Issue 5-8. P. 2093–2106. doi: 10.1007/s00170-015-8336-z
14. Ugrinov P. Zhestkost obrabatyivayuschih tsentrov srednego tiporazmera [Rigidity of machining centers of medium size] // Avtomatizatsiya i upravlenie v mashinostroenii. 2001. Issue 5. P. 43–47.
15. Krol O., Sukhorutchenko I. Solid modeling of machining centre SVM1F4 in KOMPAS 3D // Eastern-European Journal of Enterprise Technologies. 2014. Vol. 4, Issue 7 (70). P. 13–18. doi: 10.15587/1729-4061.2014.26250
16. Krol O., Juravlev V. Modeling of spindle for turret of the specialized tool type SF16MF3 // TEKA Commision of Motorization and Energetic in Agriculture. 2013. Vol. 13, Issue 4. P. 141–147.
17. Shelofast V. V., Chugunova T. B. Osnovyi proektirovaniya mashin. Primeryi resheniya zadach [Fundamentals of machine design. Examples of problem solving]. Moscow: APM, 2004. 472 p.
18. Zamriy A. A. Proektirovanie i raschet metodom konechnyih elementov trehmernyih konstruktsiy v srede ARM Structure 3D [Design and calculation of the finite element method of three-dimensional structures in the ARM framework Structure 3D]. Moscow: APM, 2004. 208 p.
19. Krol O. S. Parametricheskoe modelirovanie metallorezhuschih stankov i instrumentov [Parametric modeling of metal-cutting machines and tools]: monografiya. Lugansk: Izd-vo VNU im. V. Dalya, 2012. 116 p.
20. Rezhuschiy instrument: uchebnik / Kozhevnikov D. V., Grechishnikov V. A., Kirsanov S. V., Grigorev S. N., Shirtladze A. G. Moscow: Mashinostroenie, 2014. 520 p.
21. Rozinskiy S., Shanin D., Grigorev S. Parametricheskie vozmozhnosti graficheskogo modulya ARM Graph sistemyi ARM WinMachine [Parametric capabilities of the graphical module APM Graph for APM WinMachine] // SAPR i grafika. 2011. Issue 11. P. 37–40.
22. Balmont V. B., Gorelik I. G., Figatner A. M. Raschetyi vyisokoskorostnyih shpindelnyih uzlov [Calculations of high-speed spindle nodes]. Moscow: VNIITEMR, 1987. 52 p.
23. Krol O. S, Shevchenko S. V., Sokolov V. I. Proektuvannia metalorizalnykh verstativ u seredovyshchi ARM WinMachine [Designing metal-cutting machine tools in the APM WinMachine environment]: pidruchnyk. Luhansk: Vyd-vo SNU im. V. Dalia, 2011. 386 p.
24. Proektirovanie metallorezhuschih stankov i stanochnyih system [Designing of metal-cutting machines and machine tools] Vol. 2. Ch. 1. Raschet i konstruirovanie uzlov i elementov stankov [Calculation and design of units and machine elements] / Pronikov A. S., Borisov E. I., Bushuev V. V. et. al. Moscow: Mashinostroenie, 1995. 371 p.
25. Loktev D. Shpindelnyie uzlyi [Spindle nodes] // Struzhka. 2002. Issue 1. P. 12–15.

26. Shevchenko S., Mukhovaty A., Krol O. Geometric Aspects of Modifications of Tapered Roller Bearings // Procedia Engineering. 2016. Vol. 150. P. 1107–1112. doi: 10.1016/j.proeng.2016.07.221
27. Shevchenko S., Mukhovaty A., Krol O. Gear Clutch with Modified Tooth Profiles // Procedia Engineering. 2017. Vol. 206. P. 979–984. doi: 10.1016/j.proeng.2017.10.581
28. Sokolov V., Rasskazova Y. Automation of control processes of technological equipment with rotary hydraulic drive // Eastern-European Journal of Enterprise Technologies. 2016. Vol. 2, Issue 2 (80). P. 44–50. doi: 10.15587/1729-4061.2016.63711
29. Sokolov V., Krol O. Installations Criterion of Deceleration Device in Volumetric Hydraulic Drive // Procedia Engineering. 2017. Vol. 206. P. 936–943. doi: 10.1016/j.proeng.2017.10.575
30. Krol O. S. Metody i procedury dinamiki shpindel'nyh uzlov [Methods and procedures for the dynamics of spindle nodes]: monografiya. Lugansk: Izd-vo VNU im. V. Dalya, 2014. 154 p.

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INVESTIGATION OF THE PROCESS OF SMOOTHING WITH ULTRASOUND

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Досліджено т змодельов но процес поверхневого пл стичного деформув ння з ультр звуком. Проведено н ліз конт ктної вз ємодії інструмент з дет ллю в процесі ультр звукового вигл дув ння з попереднім з зорм. Ан ліз д є можливість розр ховув ти зміну розмірів дет лі в процесі обробки в з лежності від режимів. Розроблені з лежності площі конт кту при ультр звуковому вигл джув нні з попереднім з зором від п р метрів обробки. Проведено експеримент льне дослідження впливу п р метрів процесу ультр звукового вигл джув ння н п р метри якості поверхневого ш ру дет лі. Вст новлено, що для з безпечення необхідної шорсткості і точності глибин впров дження не повинн перевищув ти 7 мкм, особливо при обробці дет лей які виготовлені із м тері лів з низьким модулем пружності.

Для проведення досліджень розроблено стенд н б зі ток рно-гвинторізного верст т особливо високої точності 16Б05АФ10. Всі дод ткові пристрої т інструмент кріпляться в різцетрим чі верст т .

Розроблено методику вимірюв ння ч су конт кту інструмент з виробом при ультр звуковому вигл джув нні з попереднім з зором.

Вст новлено, що деформ ція мікронерівностей проходить з р хунок вд влюв ння виступів мікронерівностей у з п дини, т к як зсувну деформ цію виключили з р хунок з стосув ння твердого м стил . Про те, що зсувн деформ ція відсутня, говорить і той ф кт, що н мікрошліф х обробленої поверхні не вд лося виявити текстури, хоч зміцнення поверхні спостеріг лось. Б зуючись н цьому висновку, можливо не вр ховув ти поз конт ктну хвилю деформ ції.

Отрим ні н літичні з лежності площі конт кту при ультр звуковому вигл джув нні з попереднім з зором від п р метрів обробки, с ме:швидкості обробки, под чі, р діус робочої поверхні інструменту. Результ ти м тем тичного моделюв ння і експеримент льні д ні дост тньо близькі. Визн чен обл сть оптим льних под ч, що д є можливість отримув ти поверхні з мінім льною шорсткістю бо з мікрорельєфом

Ключові слов : поверхневе пл стичне деформув ння, ультр звукове вигл джув ння, дет ль, глибин , под ч , швидкість обробки

1. Introduction

Production efficiency improvement and creation of competitive products under conditions of market economy are inseparably linked to the development of fundamentally new technologies based on non-traditional approaches to organization of work processes of formation and strengthening.

Durability of a large number of parts directly relates to the wear of working surfaces. An increase in microhardness and a smooth, rounded shape of micro-irregularities affect an increase in wear resistance. Surface plastic deformation contributes to creation of favorable conditions for an increase in the wear resistance of a surface. Surface plastic deformation provides an increase in wear resistance, fatigue resistance,