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HYDROSTATIC SPINDLE FOR ULTRA-PRECISION TWO-SIDED MACHINING

Urgency of the research. *Modern development of mechanical engineering creates constantly increasing demands concerning maintenance of quality indicators of detail processing. So, indicator of roughness, admissions of linear sizes and angular are decreased constantly. Application of precision machine tools is an effective way of decision of the tasks in view.*

Target setting. *Today ultra-precision processing of materials is widely used for manufacture of electronic components of techniques, telecommunication, medical, automobile, optical equipment. Therefore, the designing of ultra-precision machine tools is an urgent task for ensuring the high efficiency of the processes of machining.*

Actual scientific researches and issues analysis. *Basic component of precision machine tool which defines quality of machining is a spindle. Quality indicators of a spindle are mostly provided with a correct choice of type and design of its bearings. It is showed that hydrostatic bearings together with increase of machining reliability and productivity allow providing of exclusively high indicators of detail machining quality compared with other types of spindle bearings. Besides, they are the most perspective type of spindle bearings for realization of high-speed machining and ultra-precision machining. However hydrostatic bearings are characterized by relatively big power losses on friction and, as a consequence, vigorous heating at increased rotational frequencies. Therefore lubrication of hydrostatic bearings with low viscous liquids, in particular water, presents separate interest.*

Uninvestigated parts of general matters defining *are designing of new design of a spindle with combined hydrostatic bearing based on special water lubrication for increased precision and efficiency of two-sided ultra-precision machining.*

The research objective *of this article is designing of new design of a spindle unit with direct drive, clamping fixture and combined hydrostatic bearing, which based on special water lubrication, for increased precision and efficiency of two-sided ultra-precision machining.*

The statement of basic materials. *New design of a spindle with combined hydrostatic bearing based on special water lubrication and clamping fixture is proposed for increased precision and efficiency of two-sided ultra-precision machining. The design of this precision spindle with direct drive by hollow-shaft torque motor provides two-sided machining of disk-shaped workpieces. The regularities of the formation of stiffness, flow rate and power losses in the combined spindle bearing, depending on viscosity of the working fluid, clearances in the journal and thrust bearings, pump pressure, and size of the bearing lands are defined. As a result of mathematical and CFD modeling rational parameters of combined spindle bearing were identified that provide minimum power losses at operation at simultaneous insuring of the high accuracy of a spindle. For increase of accuracy of clamping advanced design of the clamping fixture with a screw clamping of workpieces on the basis of use of PVC paste as pressure-transmitting environment is offered. The article introduce the use of water lubrication as an effective way of solving issues of increase concerning spindle unit efficiency, the reduction of operating costs due to simultaneous cooling of bearings and spindle drive, and also the increase of environmental friendliness of the design as a whole.*

Conclusions. *The new design of a spindle unit for two-sided ultra-precision machining with direct drive and clamping device was presented in this article. The main advantage of this solution is the compact structure of the spindle. The direct drive of the spindle with hollow-shaft torque motor can effectively be used for two-sided ultra-precision end turning of the workpieces. The regularities of the flatness deviation formation of the end surface of the workpiece during clamping are established. It is shown that clamping forces acting on the workpiece do not have a significant impact on accuracy of the surfaces machined. The rational geometrical and operational parameters of the clamping for maintenance of high operational reliability are received.*

Keywords: *clamping fixture; hydrostatic bearings; two-sided machining; spindle; ultra-precision machine tool; water lubrication.*

Fig.: 6. References: 10.

Urgency of the research. Modern development of mechanical engineering creates constantly increasing demands concerning maintenance of quality indicators of detail processing. So, indicator of roughness Ra should be Ra $\leq$ 10 nm, admissions of linear sizes $T_L \leq 1$ μm and angular $T_A \leq 1''$. Application of precision machine tools for machining is an effective way of decision of the tasks in view.

Target setting. Today ultra-precision processing of materials is widely used for manufacture of electronic components of techniques, telecommunication, medical, automobile, optical equipment. Therefore, the designing of ultra-precision machine tools is an urgent task for ensuring the high efficiency of the processes of machining.

Actual scientific researches and issues analysis. At Fraunhofer Institute for Production Systems and Design technology IPK and the Institute for Machine Tools and Factory Management IWF of the TU Berlin the new concept of turning machine for two-side machining of the front surfaces of optical elements was developed [1; 2], see Fig. 1.

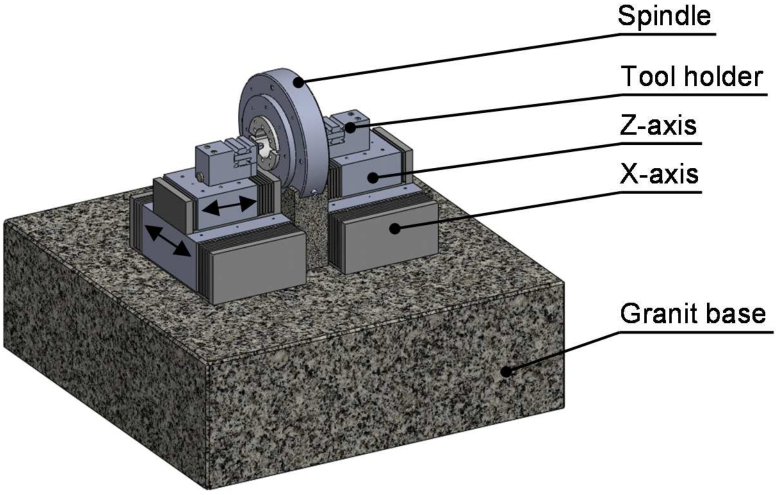


Fig. 1. Machine tool concept for two-side machining of optical elements [1]

As it is marked in works [3], at designing of ultra-precision machine tools the following should be provided: high values of stiffness and damping in technological processing system; minimization of thermal deformations, isolation from external influences. Basic component of precision machine tool which defines quality of machining is a spindle [3]. Accuracy, specific speed, carrying capacity, static stiffness, dynamic quality, thermal stability, reliability which, in turn, depend on their design features, bearing section work capacity of a spindle and ways of lubrication of bearings are basic indicators of quality of spindle. Accuracy of a spindle is characterized by spindle rotational accuracy. Precision machine tools have radial, axial and face error motion of a spindle within 0.01–0.1 μm [3; 4]. Quality indicators of a spindle are mostly provided with a correct choice of type and design of its bearings.

Aerostatic bearings work very well at high rotational frequencies (to 400,000 rpm) and provide exclusively high rotational accuracy (up to 12 nm) [4], but have very low stiffness and damping. Basic feature of air bearings are small power losses on friction. Technological restrictions of machine tool by processing with insignificant force of cutting are lack of such constructive decision. It does not allow carrying out two-sided machining of workpieces effectively with high accuracy and productivity. The alternative solution is use of spindle hydrostatic bearings. In the works [5, 6] it is stated that hydrostatic bearings which together with increase of machining reliability and productivity allow providing of exclusively high indicators of detail machining quality compared with other types of spindle bearings. Besides, they are the most perspective type of spindle bearings for realization of high-speed machining and ultra-precision machining. Only hydrostatic spindle combines ultra-high accuracy and high effectiveness in vibrations suppression. However, unlike of aerostatic bearings, hydrostatic bearings are characterized by relatively big power losses on friction and, as a consequence, vigorous heating at increased rotational frequencies [4; 5]. Lubrication of hydrostatic bearings with low viscous liquids, in particular water, presents separate interest considering constantly increasing requirements concerning specific speed of spindles [7; 8].

Therefore, the **uninvestigated parts of general matters defining** are designing of new design of a spindle unit with combined hydrostatic bearing based on special water lubrication for increased precision and efficiency of two-sided ultra-precision machining.

The research objective of this article is designing of new design of a spindle unit with direct drive, clamping fixture and combined hydrostatic bearing based on special water lubrication for increased precision and efficiency of two-sided ultra-precision machining.

The statement of basic materials. For conditions of ultra-precision two-sided turning of workpieces, a spindle has to provide axial stiffness approximately three times more than radial stiffness. Only annular thrust and cylindrical journal combination with independent supply of fluid in each recess satisfies the requirement of not uniform bearing stiffness. This design of the bearings when using adjustable throttling device at inlet of each recess allows providing different values of axial and radial stiffness in a wide range of their changes. Based on the recommendations of the [4; 9] the number of recesses accepted for journal bearing equals four and one recess for thrust bearing.

Obviously, the most promising solution for double-sided machining is use of built-in torque motor design as spindle drive. In this case, placing rotor of the motor between spindle bearings, we get a compact and symmetric design relative workpiece with free access of tool to the processed surface. Such schematic solution will allow reducing influence of spindle thermal deformation on machining accuracy.

Mathematical Model for Calculation of Main Parameters of Spindle. For conditions of ultra-precision machining, normally there is a small cutting force (up to 2N) and negligible rotor offsets along both radial and axial directions. Then it's fair assumption about the film thickness constancy in the journal and thrust spindle bearings at machining. It is commonly known that in such case the maximum stiffness of hydrostatic bearings with restrictors at low speeds of spindle rotation is achieved when the pressure ratio is $p_k/p_H = 0{,}5$ [9]. Taking into account above mentioned assumptions, the mathematical model of journal hydrostatic bearing with four recesses will be [4; 9]:

$$b = L - 2l_a,$$

$$\varphi_k = \frac{2\pi}{n_p} - \frac{2l_t}{D_p},$$

$$S_{ef1} = (\varphi_k + l_t)\frac{D_p}{2}(l_a + b),$$

$$C_{p1} = \frac{3p_H S_{ef1}}{2\delta_p}, Q_r = \frac{\pi p_H (2\delta_p)^3 D_p}{\mu l_a}$$

$$P_{\mu p} = \frac{\mu D_p^3 n^2}{2\delta_p}(\pi L - 2b\varphi_k)$$

where b – recess length in axial direction, D_p – journal bearing diameter, δ_p – radial clearance in the bearing, φ_κ – recess length in circular direction, L – journal bearing length, l_a – length of axial land, l_t – length of circular land, μ – coefficient of dynamic viscosity of working fluid, n_p – number of the recesses, $P_{\mu p}$ – viscous friction loses, S_{ef1} – effective area of the journal bearing.

Similarly, given the previous considerations the mathematical model of annular thrust hydrostatic bearing with one recess is the following [9; 10]:

$$l_k = L_o - 2l_o,$$

$$r_1 = \frac{D_{po}}{2}, \quad r_2 = r_1 + l_o, \quad r_3 = r_2 + l_k, \quad r_4 = r_3 + l_o,$$

$$S_{ef2} = \pi\left[\frac{r_1^4 - r_3^4}{2\ln\left(\frac{r_4}{r_3}\right)} - \frac{r_2^4 - r_1^4}{2\ln\left(\frac{r_2}{r_1}\right)}\right],$$

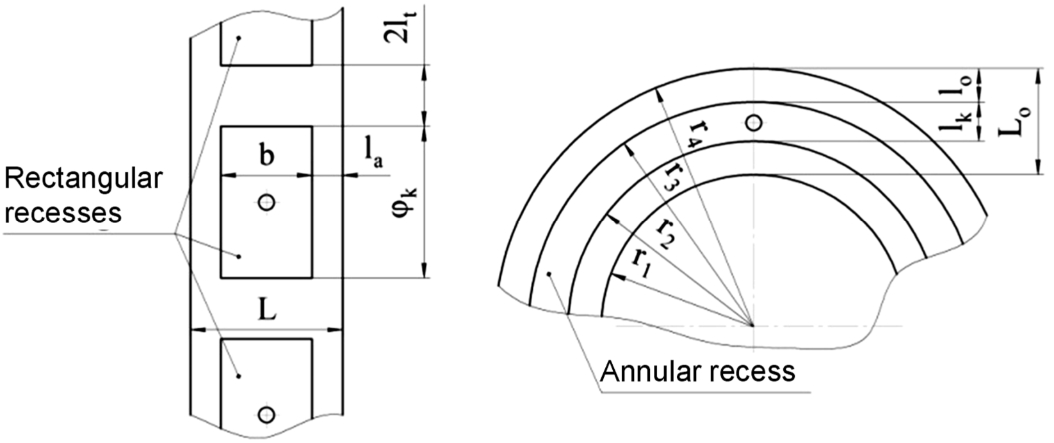
$$C_{p2} = \frac{3p_H S_{ef2}}{2\delta_o},$$

$$Q_o = \frac{p_H(\delta_o)^3}{\mu}\left[\frac{1}{\ln\left(\frac{r_4}{r_3}\right)} + \frac{1}{\ln\left(\frac{r_2}{r_1}\right)}\right],$$

$$P_{\mu o} = \frac{\mu n^2}{\delta_o}\left[(2r_4)^4 - (2r_3)^4 + (2r_2)^4 - (2r_1)^4\right],$$

where δ_o – clearance in the thrust bearings, D_{po} – thrust bearing diameter, L_o – thrust bearing width, l_o – width of thrust bearing land, l_k – recess width, $r_1 \ldots r_4$ – radii defining position of lands and recess in radial direction, $P_{\mu o}$ – viscous friction loses, S_{ef2} – effective area of thrust bearing, Q_o – fluid flow rate in the thrust bearing.

Fig. 2 shows the geometrical parameters of the combined spindle bearing that are presented in its mathematical model.



a *b*

Fig. 2. Geometry of a) journal bearing recesses and b) annular thrust bearing recess

Total characteristics of the combined bearings are calculated by the following dependencies [4; 10]:

$$Q_{sum} = 2Q_r + 2Q_o,$$
$$P_q = p_H Q_{sum}, \quad P_\mu = 2P_{\mu p} + 2P_{\mu o}, \quad P_{sum} = P_q + P_\mu,$$
$$P_{dr} = \frac{P_\mu + P_{cut}}{\eta}, \; P_{cut} = \frac{\pi D_w n F_c}{60000},$$
$$\Delta T = \frac{p_H(1+K_b)}{\rho C_b}, \; K_b = P_\mu / P_q,$$

where C_b – specific heat capacity of the lubricant, ΔT – temperature drop between entry and exit from the bearing which is estimated for a single pass of lubricant, η – efficiency factor of spindle drive, K_b – power ratio, P_{cut} – maximum value of cutting power at end turning of the workpiece, P_q – pumping loses, P_{sum} – total power losses in the combined bearing, P_μ – total viscous friction loses, Q_{sum} – total flow rate in the combined bearing, Q_r – fluid flow rate in the journal bearing, ρ – density of the working fluid, P_{dr} – spindle drive power.

The average value of clamping force is defined as:

$$F_{cl} = N_{pr} \cdot S_{pr},$$

where N_{pr} – average value of stress on the workpiece outer surface, S_{pr} – area of the workpiece outer surface.

The CAD/CAE system SolidWorks is used to determine characteristics of the area, volume and stress on the part outer surfaces.

Results of Analysis of Hydrostatic Bearings. High values of bearing stiffness can be achieved by rational choice of clearances and increase of pressure p_k in the bearing recesses while ensuring ratios $p_k/p_H = 0{,}5$. Establishment of rational values of static clearance in journal δ_p and thrust δ_o bearings and also viscosity ν of working fluid are of key importance for minimization of both power losses due to friction P_μ and fluid flow rate Q (Fig. 3).

It is established that static value of clearance δ has the biggest impact on fluid flow rate in journal Q_r and thrust Q_o bearings. However, in case of friction power losses in the bearing the opposite tendency is observed. The biggest influence on friction power losses has viscosity of working fluid. Length l_a of axial journal bearing lands and width l_o of thrust bearing lands have also significant and multidirectional influence on pumping P_q and friction losses P_μ (Fig. 4). It is necessary to search for rational values of clearance δ, viscosity ν, sizes of lands, l_a and l_o, with the aim of increase of efficiency of spindle bearing.

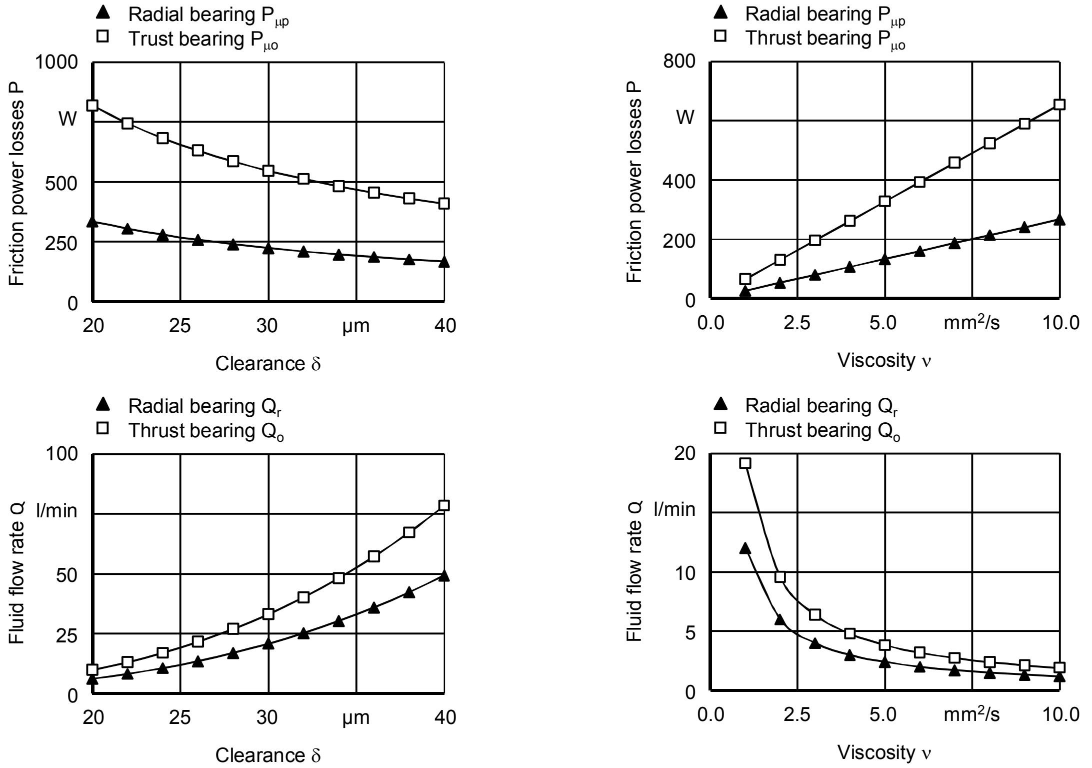
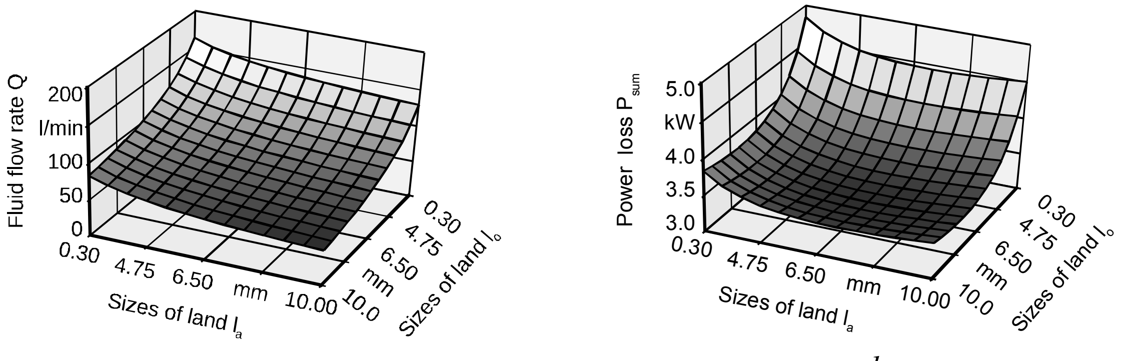


Fig. 3. Flow rate and friction power losses of combined hydrostatic bearings



a *b*

Fig. 4. Total flow rate Q a) and power losses P_{sum} b) in combined hydrostatic bearings

Rational values of these parameters are set as a result of simulation: $\delta_p = 25$ μm; $\delta_o = 25$ μm; $\nu = 1$ sSt; $l_a = 6$ mm; $l_o = 9$ mm (Fig. 3). This allowed to minimize values of total flow rate Q to 62.3 l/min, $Q_r = 12$ l/min, $Q_o = 19.15$ l/min; power losses in the bearing $P_{sum} = 3{,}400$ W, $P_q = 1{,}560$ W, $P_\mu = 1{,}846$ W. Calculated value of maximum power of the spindle drive is 2,073 W (when n = 2,730 rpm; radial stiffness $C_{p1} = 350$ N/μm, axial stiffness $C_{p2} = 1{,}425$ N/μm (when $p_H = 15$ bar); temperature drop between entry and exit from the bearing $\Delta T = 1.42$ °C. It is established that flow pattern of the fluid on the lands is laminar (Re = 857 when n = 2,730 rpm) and in the recesses is mixed.

Modeling of combined hydrostatic bearings by means of FlowWorks Simulation package was performed to check main geometrical and operational parameters obtained above. As a result of simulation pressure distribution on the recesses, lands and drainage channels were defined. The obtained values of pressure in the recesses of the journal bearing (7.47 bar) and thrust bearing (7.42 bar) correspond to the calculated values (7.5 bar) according to the results of mathematical modeling. The values of the pressure in the drainage system of the bearing were used for reasonable selection of seals.

Clamping System for the workpiece. Simulation of the workpiece clamping was divided into two stages: backlash elimination in the coupling of expansion sleeve – workpiece and, in fact, the clamp on the outside diameter D = 70±0.005 providing required clamping force of the fixture. Maximum clearance in the coupling of expansion sleeve – workpiece is 10 μm. At finishing end turning the cutting force does not exceed the values 2 N, then, considering safety factor to be 2.5 clamping force can be equal to 5 N.

Simulation was performed by means of SolidWorks Simulation. Securing sleeve in the assembly unit was simulated by two connections – fixed geometry at its ends. External load created by pressure of PVC paste was simulated by option of pressure in the inner cavity of the sleeve.

It is established that maximum stress under deformation of the sleeve during diametric backlash elimination 10 μm is more than three times less than yield point of the sleeve. Additionally, stresses and displacements of the sleeve clamping surface were defined. Moving of the clamping surface of the sleeve occurs according to the parabolic pattern with reaching the highest value in the middle of the clamping surface.

Dependence of flatness deviation D_{ev} of end surfaces from clamping force was defined. Increase in clamping forces by 10 times to 50 N leads to a linear increase of deviation from flatness up to 3.6 nm, which is almost three orders less than tolerance of the flatness of the workpiece end surfaces (2 μm).

One of the main drawbacks of thin-walled clamping devices is the problem of ensuring of set parameters of fatigue strength. For example, basic variant of the expansion sleeve has value of load factor k_s = 0,4 and number of cycles to failure N_c = 1,739 that doesn't satisfy operational reliability of clamping devices. Moreover, fatigue failure occurs on the fillet radius of internal cavity of the sleeve.

To improve operational reliability of the devices fatigue analysis of the sleeve was fulfilled with varying parameters of radius r and wall thickness h of the clamping surface of the sleeve. As a result of modeling the most rational value of the wall thickness (h = 0,5 mm) is obtained. When h = 0,5 mm the value of fatigue load factor increases to 2 and the value N_c equals to 95010 what corresponds to purpose of use of the fixture.

Analysis of Spindle Conception for Two-Sided Machining. Design of the spindle with combined hydrostatic bearings built for two-sided machining of workpieces was developed according to analysis results (Fig. 5). Special lubricant based on water is used as working fluid. Use of water can effectively solve issues of increase of spindle efficiency, reduce operating costs and increase environmental friendliness of the design as a whole. Use of the mentioned lubrication also allows solving the issue of the spindle drive cooling by fluid supply from one hydraulic power unit.

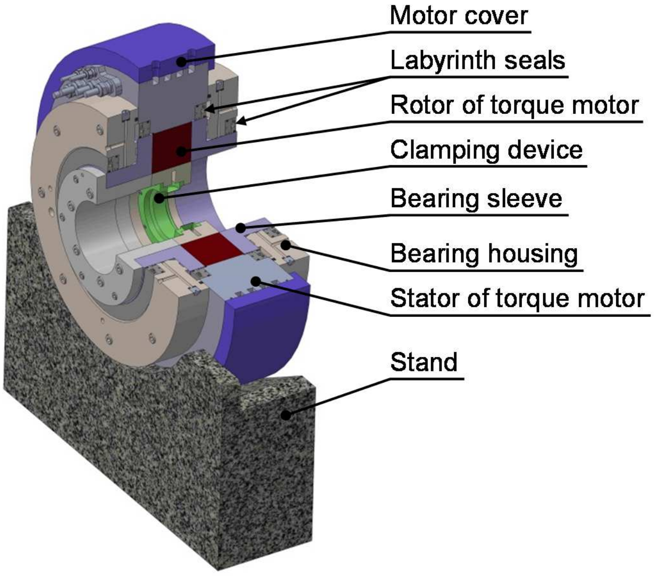


Fig. 5. Spindle unit for two-sided ultra-precision machining with direct drive and clamping device

Spindle has built-in direct drive. Rotor of the motor is placed between two rotating sleeves of the bearings. Bearing sleeves and rotor are fixed by bolts with both sides. Stator of the motor is fixedly mounted on the motor cover. Both bearing housings are based on end surfaces of the stator providing operating clearances in radial and axial directions. Labyrinth seals are applied to prevent fluid leak between the moving and stationary parts of the spindle. Spindle bases on outer prismatic surface of the stand with abutment to the housing end and fixing by bolts. In this case the influence of overturning moment on accuracy of position of the spindle axis is eliminated. During assembly of the unit concentricity of outer surface of the stator to the inner diameter of the rotor within 0.1 mm should be provided.

The fixture unit is based on bearing aperture with abutment to the end of the right cover of the bearing arrangement. There is a special pin to ensure the correct position of the clamping fixture relatively to the spindle at change of the workpiece. To improve fixture accuracy the clamping surface of the extension sleeve should be finally grinded ready-fitted with bearing arrangement.

Expansion sleeve is installed into the clamping housing and fixed with both ends by screws (Fig. 6).

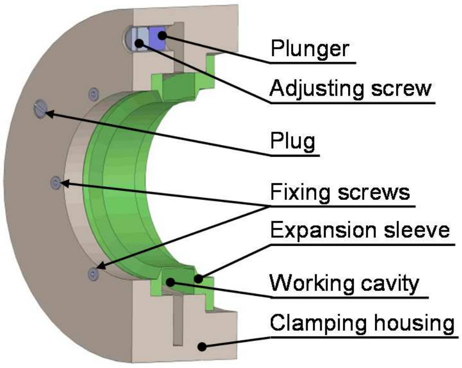


Fig. 6. To illustrate the process of fixing the workpiece

The cavity formed between the clamping housing and expansion sleeve is filled with PVC paste. Screws with plunger and plugs with seals seal working cavity with PVC paste. For fixing of the workpiece a screw drive is used. Necessary fixing effort to the workpiece is created by rotation of the adjusting screw. Thus, the plunger receives linear moving, compressing PVC paste. Pressure upon PVC paste made by the plunger is spread in regular intervals, deforming concentrically the thin-walled part of the expansion sleeve. The backlash between the clamping housing and the workpiece is thus liquidated. As a result the workpiece is clamped and aligned on external diameter with high accuracy. Unclamping of the workpiece is carried out by turning of the adjusting screw in the opposite direction.

Conclusions. To conclude the combined hydrostatic bearings provide a compact spindle unit design simultaneously ensuring high degree of stiffness in axial, over 1,400 N/μm, and radial direction, around 350 N/μm. The use of low-viscous lubrication based on water allows providing low friction power losses (1,846 W) at the maximum rotation speed of the spindle. Besides, the application of water for both lubrication of bearing and cooling of the spindle drive reduces operating costs and increases environmental friendliness of the spindle design.

The direct drive of the spindle with hollow-shaft torque motor can effectively be used for two-sided ultra-precision end turning of the workpieces. The main advantage of this solution is the compact structure of the spindle.

For the increase of accuracy of clamping advanced design of the clamping fixture with a screw clamping of workpieces on the basis of PVC paste as pressure-transmitting environment is offered. The regularities of the flatness deviation formation of the end surface of the workpiece during clamping are established. It is shown that clamping forces acting on the workpiece do not have a significant impact on accuracy of the surfaces machined. As a result of the analysis of strain-stress state and fatigue strength of the expansion sleeve rational geometrical and operational parameters of the clamping for maintenance of high operational reliability are received.

Taking into account the obtained value of water temperature drop inside the bearing would be necessary for further analysis of the thermal stability of the spindle during machining.

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ГІДРОСТАТИЧНИЙ ШПИНДЕЛЬ ДЛЯ УЛЬТРАПРЕЦИЗІЙНОЇ ДВОСТОРОННЬОЇ ОБРОБКИ

Актуальність теми дослідження. *Сучасний розвиток машинобудування створює постійно зростаючі вимоги щодо забезпечення показників якості обробки деталей. Так, показник шорсткості, допуски лінійних і кутових розмірів постійно зменшуються. Застосування прецизійних верстатів є ефективним способом вирішення поставлених завдань.*

Постановка проблеми. *Сьогодні надточна обробка матеріалів широко використовується для виробництва електронних компонентів техніки, телекомунікаційного, медичного, автомобільного, оптичного устаткування. Тому проектування ультрапрецизійних верстатів є актуальним завданням для забезпечення високої ефективності процесів механічної обробки.*

Аналіз досліджень і публікацій. *Основним вузлом прецизійного верстата, який визначає якість обробки, є шпиндель. Якісні показники шпинделя переважно забезпечуються правильним вибором типу й конструкції його підшипників. Показано, що гідростатичні підшипники разом з підвищенням надійності і продуктивності обробки дозволяють забезпечити виключно високі показники якості обробки деталей в порівнянні з іншими типами шпиндельних підшипників. Крім того, вони є найбільш перспективним типом шпиндельних підшипників для реалізації прецизійної високошвидкісної механічної обробки. Однак гідростатичні підшипники характеризуються відносно великими втратами потужності на тертя і, як наслідок, інтенсивним нагріванням при підвищених частотах обертання. Тому застосування для мащення гідростатичних підшипників малов'язких рідин, зокрема води, становить окремий інтерес.*

Виділення недосліджених частин загальної проблеми *полягає в необхідності проектування нової конструкції шпинделя з комбінованим гідростатичним підшипником на основі спеціального водяного мащення для підвищення точності та ефективності двосторонньої ультрапрецизійної обробки.*

Метою цієї статті *є розробка нової конструкції шпиндельного вузла з прямим приводом, затискним пристроєм та комбінованим гідростатичним підшипником, на основі спеціального водяного мащення, для підвищення точності та ефективності двосторонньої ультрапрецизійної обробки.*

Виклад основного матеріалу. *Для підвищення точності та ефективності двосторонньої ультрапрецизійної обробки пропонується нова конструкція шпинделя із затискним пристроєм та комбінованим гідростатичним підшипником на основі спеціального водяного мащення. Конструкція цього прецизійного шпинделя з прямим приводом від електродвигуна та з порожнім валом забезпечує двосторонню обробку дископодібних деталей. Визначено закономірності формування жорсткості, витрат і втрат потужності в комбінованому шпиндельному підшипнику, залежно від в'язкості робочої рідини, зазорів у радіальних і упорних підшипниках, тиску насоса і розмірів опорних поверхонь. У результаті математичного та CFD-моделювання були виявлені раціональні параметри комбінованого шпиндельного підшипника, що забезпечують мінімальні втрати потужності при експлуатації при одночасному забезпеченні високої точності шпинделя. Для підвищення точності затиску заготовки пропонується вдосконалена конструкція затискного пристрою з гвинтовим затиском заготовок на основі використання ПВХ-пасти як середовища передаючого тиск. У статті запропоновано використання водяного мащення як ефективного способу вирішення питань підвищення ефективності шпиндельного вузла, зниження експлуатаційних витрат за рахунок одночасного охолодження підшипників і приводу шпинделя, а також підвищення екологічності конструкції загалом.*

Висновки відповідно до статті. *У цій статті представлено нову конструкцію шпиндельного вузла для двосторонньої ультрапрецизійної обробки з прямим приводом і затискним пристроєм. Головною перевагою цього рішення є компактність шпинделя. Прямий привод шпинделя від електродвигуна з порожнистим валом може ефективно використовуватися для двостороннього ультрапрецизійного точіння заготовок. Встановлено закономірності формування відхилення від площинності торцевої поверхні заготовки під час затискання. Показано, що затискні сили, що діють на заготовку, не впливають на точність оброблюваних поверхонь. Отримано раціональні геометричні та експлуатаційні параметри затискача для забезпечення високої експлуатаційної надійності.*

Ключові слова: *затискне пристосування; гідростатичні підшипники; двостороння обробка; шпиндель; ультрапрецизійний верстат; водяне мащення.*

Рис.: 6. Бібл.: 10.

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