UDC 621.9.06-529-8
DOI: 10.15587/1729-4061.2019.164091

INVESTIGATION OF THE INFLUENCE OF HARDNESS CHARACTERISTICS OF THE COLLET-PART LATHE SYSTEM

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Наведені результати дослідження характеристик жорсткості системи патрон-деталь токарного верстату, які є суттєво нелінійними і впливають на демпфуючі параметри шпиндельного вузла в цілому.

Метою роботи є дослідження характеристик нелінійної жорсткості елементів технологічної системи патрон-деталь. Для реалізації цієї мети в процесі експериментальних досліджень визначені статичні та динамічні характеристики жорсткості шпиндельного вузла, які являють собою петлеподні гістерезисні криві, які характерні механічним системам з великою кількістю зв'язків.

Проведено вимірювання нелінійних параметрів жорсткості системи патрон- деталь. Виміри здійснено по оригінальній методиці. Основу методики складає багатоциклове знакозмінне статичне навантаження шпинделя в зоні обробки в напрямку вектора динамічної складової сили різання розробленим оснащенням. Оснащення включає гвинтовий навантажувальний пристрій, кільцевий двохсторонній динамометр та оправку, встановлену в шпинделі верстата. В результаті проведення досліджень визначенні особливості нелінійних характеристик жорсткості системи патрон-деталь токарного верстату. Для системи патрон-деталь ширина петлі гістерезису в холодному стані може досягати 20…70 мкм. Гістерезисні характеристики системи патрон-деталь в розігрітому стані мають ширину петлі гістерезиса 50…200 мкм при затиску деталі діаметром 80…115 мм на вильоті 100…120 мм. Розроблені рекомендацій по оцінці межі зміни жорсткості в залежності конструкції патрона. Запропонована методика дозволяє в одному кутовому положенні патрона вимірювати відтискування за схемою навантаження «на кулачок» і «між кулачками», що в два рази зменшує обсяг експериментальних досліджень

Ключові слова: металорізальний верстат, затискний патрон, деталь, жорсткість затиску, пружна система, конструкція оснащення

1. Introduction

Requirements for improving the accuracy of machining parts are constantly increasing, and this trend is quite important for the development of modern production. Improving the accuracy of machining on a lathe requires the determination of the nonlinear characteristics of the hardness of the main elements of the elastic system of the machine, including the collet-part system. The accuracy of machining is mainly influenced by the hardness and accuracy of the spindle and the collet of the machine. The approximate reduced hardness of the collet-part system to the axis or the diameter of the clamp with the construction of the matrix of the radial hardness of the collet-part system is determined theoretically. The exact hardness parameters are determined, as a rule, by an experimental method under the load of the spindle and collet. The characteristics of the elastic system of the machine, including the collet, are non-linear, since they contain a large number of pairs of contact with various types of contact and interaction.

2. Literature review and problem statement

Requirements for improving the accuracy of machining parts are constantly increasing, and this trend is quite important for the development of modern production. Progress in the field of mechanical engineering and machine tool construction has contributed to the deepening study of methods and processes that allow us to describe and determine the hardness of the clamping collets. The study of various types of clamping collets showed that the total deformation of the collet-part system exposed to shearing force is more dependent on the surface deformation at the joints of kinematic pairs than on the internal deformations of the collet parts [1, 2]. For engineering calculations, you can use the concept of the unit hardness of the collet-part system to the axis or to the diameter of the clamp [1]. The total reduced hardness is determined taking into account the parallel and series connection of hardness by the element of the collet. In [3], the stress state of the collet due to changes in the conditions of friction, forces and nonlinear characteristics of the joints and mates under conditions of complex deformation was investigated. However, it should be noted that in this work the conditions for the implementation of the load are not given. Scientists in [4] introduced the concept of differential hardness of the workpiece. When calculating the required minimum clamping force, all the loads while clamping the workpiece are taken into account simultaneously. The accuracy of the new model for calculating clamping forces clearly exceeds the accuracy of previous approaches to the calculation. But from a practical point of view, this may cause certain difficulties in the calculations. In [5], parametric instability in the process of clamping collet operation is investigated. An analytical stability criterion is given and experimental confirmation is performed. Parametric oscillations are generated by the directed hardness of the collet-part system. To overcome this problem, a technique described in [6] compensates machining errors resulting from clamping with cams, taking into account their hardness and changes in the radial hardness of the clamping collet system. The study [7] analyzed the cutting process under various clamping conditions and developed a mathematical model to predict the shape of the machined part depending on the type and hardness of the clamping collet. Experimental results are in good agreement with theoretical calculations. In [8], tests on the radial and bending hardness of the collet-part system for various ratios of the cam and part diameters, cutting force positions with respect to cams and their bore angles were performed. In [9], all the main factors affecting the accuracy of machining parts in the collet were determined by budgeting errors and systematic measurements. From the results, an error map was developed, which concludes a link between these factors, including hardness of the collet, and their influence on the error of machining the part. In [10], a collet that measures the clamping forces on the workpiece during cutting was developed. A special cam using the finite element method was designed. That made possible to find a correlation between the deviations of the workpiece and the clamping force. In [11], the critical bending force and the radial hardness of the collet clamp and ways to improve it are investigated. Despite the practical significance of such results, the nonlinear characteristics of the hardness of the collet-part technological system have not been adequately considered. The paper [12] presents calculations to determine the optimal clamping force in the collet. Achieving a minimum but safe clamping force is the key in controlling the clamping process. The methodology takes into account the model of volumetric deformation, local contact stresses and experimental data in order to obtain the optimum torque applied to the cartridge.

In the literature, no reliable methods were found for determining the nonlinear hardness parameters of the collet-part technological system. Therefore, there is the reason to believe that the insufficient study of the nonlinear hardness of the collet-part technological system determines the need for further research of the problem.

3. The aim and objectives of the study

The aim of these studies is to determine and investigate the magnitude and characteristics of the nonlinear hardness of the elements of the technological system spindle – collet of the lathe. This will give the opportunity to use the results obtained when designing spindle assemblies of lathes with improved damping characteristics.

To achieve this goal, the following tasks were solved:

– to develop methods and equipment for experimental research;

– to determine the peculiarities of the formation of nonlinear deformations of the collet-part system;

– determine and estimate the hardness of each cam of the clamping collet separately.

4. Materials and methods of investigation of the collet-part system nonlinear deformations

The studies were carried out with specially developed technique and equipment. This technique was used to perform experimental studies of the nonlinear hardness characteristics of the technological system of the lathe. The results of experimental studies of the spindle hardness and the plunger collet-part system of the lathe made possible to determine their nonlinear hardness parameters.

Experimental studies of the nonlinear hardness characteristics of the technological system were carried out on a new lathe in the assembly shop. The front spindle bearing section has a two-row roller bearing 1, the rear bearing is a single-row roller bearing 2. The bearing 1 of the front bearing is tensioned by nut 3. The tension force is transferred to the bearing by sleeve 4, which has devices that fix it against rotation (Fig. 1).

At the front end of the spindle there is a three-plunger collet, which consists of workholder's body 5, in the sloped at an angle of 20° holes there are three plungers 6, the front ends of which are provided with clamping elements 7. The diameter of the clamping elements is 98 mm, the diameter of the workholder's body is 150 mm. It is closed with a lid at the end – stop 8 to install the part 15. Plungers 6 are interconnected and the machine drive is driven by piston 9 and sleeve 10. Clamping of part 15 in the collet is performed using a coil spring 12, the other spring 13 is used when braking the spindle.

Unclamping is performed by a pneumatic rotating double-acting cylinder. Compressed air in the chamber of the pneumatic cylinder is supplied through a special sleeve, which is fixed with the rotation of the rod. The pneumatic cylinder rod is connected by a draw rod 14, which consists of two parts, with a draw rod 11 of the collet. The number of mates with different elastic-dissipative connections in the collet-part system is 17 surfaces.

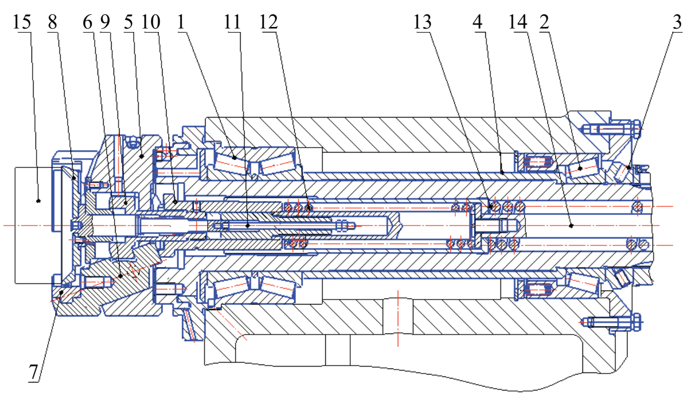

Fig. 1. Design scheme of the spindle unit with a clamping collet

To determine the deformability, an experimental study of the stochastic parameters of the static hardness of the collet-part system was conducted. In the process of experimental studies, the static characteristics of the collet-part system are defined. Measurements of nonlinear parameters of spindle hardness were carried out. When measuring indicators of static hardness, special equipment was used. Measurements were carried out by a special technique. The basis of the technique is a multi-cycle alternating static spindle load in the cutting zone towards the vector of the dynamic component of cutting force by specially designed equipment. The equipment includes a screw loading device 1, an annular double-sided dynamometer 2 and a mandrel 3 installed in the collet of the machine tool (Fig. 2).

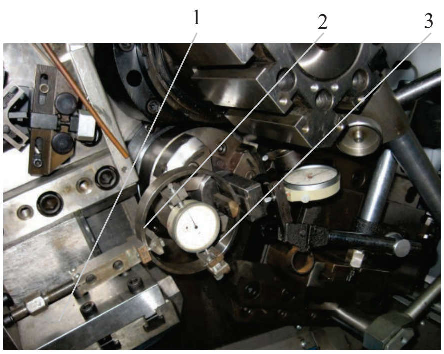

Fig. 2. Arrangement of equipment (the fitting) in the working area of the machine tool

The screw loading device for experimental studies contains an L-shaped load bracket, which is placed on the transverse support. As a power load device, a screw-nut transfer slip is used, and the screw is made with two threaded surfaces: the left and, accordingly, the right-hand thread. The left end of the screw is fixed in a special L-shaped cargo bracket mounted on the transverse support of the machine tool. The right end of the screw is associated with the possibility of self-tuning with an annular two-way dynamometer.

Ensuring the process of alternating load is carried out by a special annular two-way dynamometer. The other end of the dynamometer is fixed on the axis of the special mandrel (Fig. 3), fixed toughly in the collet of the machine tool. All connections in the kinematic equipment chains are made without backlash with clearance selection. The developed technique takes into account random changes in the hardness parameters of the spindle and the collet of the machine tool. By point values, graphs of hysteresis deformability characteristics of elastic systems are plotted.

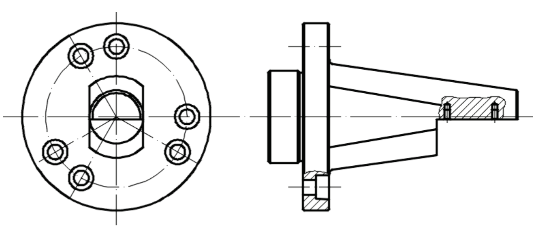

Fig. 3. Design of the mandrel for research

The alternating load module does not exceed the maximum change in the dynamic component of the shearing force. The annular dynamometer allows two-sided loads ranging from −1.200 N to 1.200 N with a range of −5 kN...5 kN, i. e. 24 points within one loading cycle. When the spindle-collet-part system is loaded with indicators I1 and I2, the absolute displacement of the spindle and mandrel is measured with a 0.001 mm division value. The arrangement of equipment and measuring instruments in the working area of the machine is shown in Fig. 2, the design of the mandrel for research in Fig. 3, the measurement scheme – in Fig. 4. The loading of the mandrel in the collet was carried out according to the scheme: the force is applied to the cam and between the cams. In one position of the load device, it is possible to perform measurements using both loading schemes.

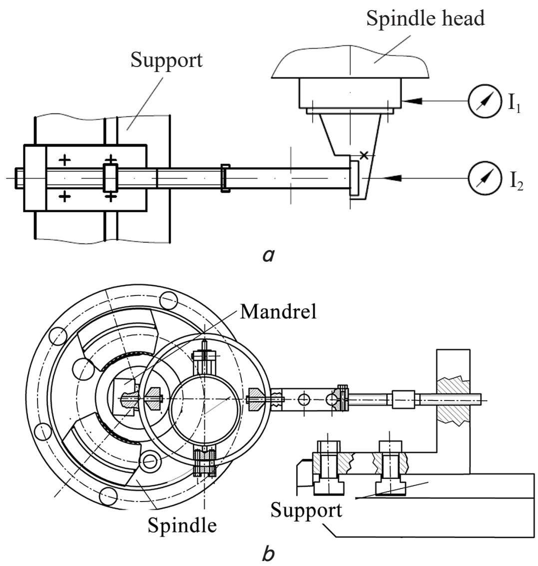

Fig. 4. Loading and measurement scheme: *a* – a view of the working area in the plan, *b* – a side view

At the same time, the radial moving of the cartridge at point I_1 and the mandrel at point I_2 is registered. Measurements of a significant number of load cycles (about 15) were carried out. The number of measurement points was about 400.

5. Results of studies of nonlinear hardness parameters of the collet-part system.

5. 1. Description of the elastic collet-part system

The hardness of the collet, its assembly units or component parts characterizes their elastic deformations and behavior under the influence of external forces and moments, resistance to changes in their shape and position. For various modes of load and deformation, the corresponding hardness and compliance are decisive.

When machining the workpiece in the collet on the clamping surface of the cam, the required clamping force is created, and axial and tangential forces arise. The deformed state and behavior of the clamping collet system, as a rule, can be completely described in general terms by a hardness matrix with nine kinds of hardness, which characterize the corresponding movements along the coordinate axes, and nine angular kinds of hardness [4].

The study considers a linear relationship, which is valid only for small values of elastic displacements and in the case of static load.

Since the contact deformations at the joints largely depend on the quality of the surface (accuracy, surface shape and roughness of the contacting surfaces) and are random, for an objective assessment not only of the design of the collet, but also the quality of its manufacture, hardness should be controlled for each collet separately in addition to the accuracy test. At the same time, the technological system of the machine tool is a closed dynamic system capable of exciting and maintaining the vibrations causing the shape errors of the surfaces to be machined (out-of-roundness, waviness) and increase their roughness.

Theoretically, it is not possible to calculate the hardness of the technological system due to the stochastic nature of the manifestation of the operational properties of the contacting surfaces, as well as the actual dimensions of the guaranteed clearances. Therefore, the hardness of the elements of the technological system of machine tools (hardness of the spindle, collet, etc.) is mainly determined experimentally and based on the obtained experimental data, mathematical models which are the basis for analyzing and determining the necessary measures to develop recommendations for improving the hardness of the machine tool and processing accuracy.

5. 2. Construction of hardness characteristics of the collet-part system

The obtained results are processed according to the developed method, which includes the statistical processing of repeated loading and linearization of the results of stiffness description. The processing of the measurement results allowed determining the hysteresis loop parameters when moving the elements of the cartridge-part system under the action of the radial alternating force, imitating the cutting force. The force was applied in the direction of the vector of the dynamic component of the cutting force.

As a result of experiments, the point values of the displacement of the collet-part system were determined at a cyclic change in force when loading on the cam and between the cams. The load device, which originality was alternating load, was designed. The graphs for the absolute movement of the collet and the part look like loop-shaped hysteresis curves. The hysteresis characteristics of the collet clamp are substantially nonlinear, the width of the hysteresis loop can reach 50...200 μm.

Based on the experimental studies, a model of the spatial displacements of the elements of the collet is built (Fig. 7).

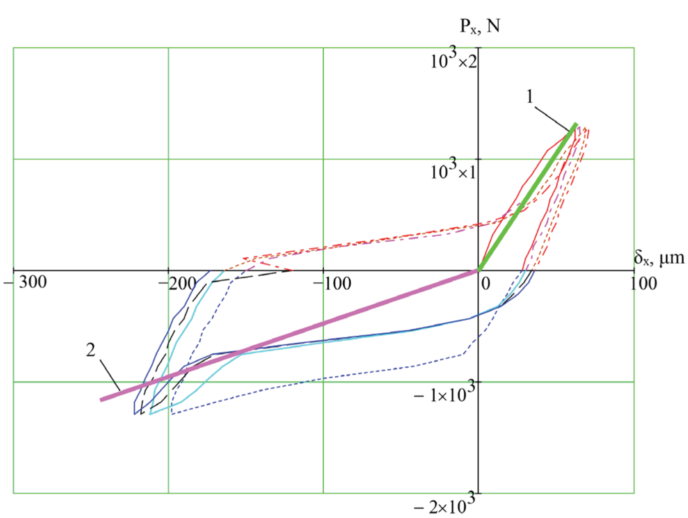

Fig. 5. Deformation of the cartridge-part system:
1 – when loading on the cam, 2 – when loading between the cams

Consider elastic displacements in the *XOY* plane under the action of loads $\bar{F}=(P_x,P_y)^{\mathrm{T}}$ and $\bar{M}=(M_x,M_y)^{\mathrm{T}}$. The clamping elements when exposed to these loads are deformed (contact hardness) and reactive forces and moments emerge in them. Consider the deformation of the *i*-th linear-elastic clamping element.

Reactive force:

$$\bar{P}_i=-K_i\cdot\Delta_i\cdot\bar{\alpha}_i. \tag{1}$$

The moment of the vector $\bar{P}_i$ relative to the coordinate origin:

$$\bar{M}_i=\bar{r}_i\cdot\bar{P}_i=-K_i\cdot\Delta_i\cdot(\bar{r}_i\cdot\bar{q}_i). \tag{2}$$

The amount of deformation:

$$\Delta_i=\delta\bar{r}_i\cdot\bar{\alpha}_i=(\varepsilon\cdot\bar{r}_i)\cdot\bar{\alpha}_i, \tag{3}$$

where ε is a 4×4 matrix of the generalized error of the position of the clamping element:

$$\varepsilon=\begin{vmatrix}0 & 0 & \beta & \delta_x\\ 0 & 0 & -\alpha & \delta_y\\ -\beta & \alpha & 0 & 0\\ 0 & 0 & 0 & 0\end{vmatrix}, \tag{4}$$

where δ_x, δ_y are small displacements of center 0 along the *OX*, *OY* axes, respectively, α, β are small angles of rotation of the *OXYZ* system relative to the *OX*, *OY* axes.

Find the reactive forces and moments that occur in the cams when clamping the workpiece. Take the origin of the *OX* rotation axis. Using the expanded rotation matrix about the *OZ* axis, we have:

$$R_z(\varphi)=\begin{vmatrix}\cos\varphi & -\sin\varphi & 0 & 0\\ \sin\varphi & \cos\varphi & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{vmatrix}. \tag{5}$$

Find the coordinates of the radius vectors $\bar{r}_i$ of the fixing points of the workpiece and the unit vectors of their hardness $\bar{\alpha}_i$:

$$\bar{\alpha}_i=R_z(\varphi)\cdot\bar{\alpha}_x,$$

where $\bar{\alpha}_x=[1,0,0,0]^{\mathrm{T}}$ is the unit vector of the *OX* axis φ_i is the angle that determines the position of the clamping point by the *i*-cam; φ is the angle of rotation relative to the *OZ* axis.

We write the equilibrium equation of the system:

$$\begin{cases}\sum\limits_{i=1}^{3}\bar{P}_i+\bar{F}=0,\\ \sum\limits_{i=1}^{3}\bar{M}_i+\bar{M}=0,\end{cases} \tag{6}$$

where $\bar{F}=[P_x,P_y,0,0]^{\mathrm{T}}$ is the main vector of the system of external loads, $\bar{M}=[M_x,M_y,0,0]^{\mathrm{T}}$ is the main moment of the system of external loads or in the expanded form:

$$\begin{cases} P_x + \sum_{i=1}^{3} Kr_i \cdot (\delta_x \cdot \cos\varphi_i + \delta_y \cdot \sin\varphi_i) \cdot \cos\varphi_i = 0, \\ P_y + \sum_{i=1}^{3} Kr_i \cdot (\delta_x \cdot \cos\varphi_i + \delta_y \cdot \sin\varphi_i) \cdot \sin\varphi_i = 0, \\ M_x + \sum_{i=1}^{3} K_{ni} \cdot (\alpha \cdot \cos\varphi_i + \beta \cdot \sin\varphi_i) \cdot \cos\varphi_i = 0, \\ M_y + \sum_{i=1}^{3} K_{ni} \cdot (\alpha \cdot \cos\varphi_i + \beta \cdot \sin\varphi_i) \cdot \sin\varphi_i = 0. \end{cases} \quad (7)$$

The solution of this system of equations will give the value of small displacements and turns $(\delta_x, \delta_y, \alpha, \beta)$ of the workpiece under the action of the combined load (P_x, P_y, M_x, M_y). We write equation (7) in the form:

$$\bar{\delta} = [D][P],$$

where

$$D = \begin{bmatrix} C_x & C_{yx} \\ C_{xy} & C_y \end{bmatrix}$$

– linear compliance matrix;

$$D = [K]^{-1} = \det[K] \cdot \begin{vmatrix} \Delta_{11} & \Delta_{12} \\ \Delta_{21} & \Delta_{22} \end{vmatrix}^{T}, \quad (8)$$

where Δ_{ij} is the algebraic complement of the matrix $[K]$, $\Delta_{11} = k_y$; $\Delta_{12} = k_{xy}$; $\Delta_{21} = k_{xy}$; $\Delta_{22} = k_x$, $\det[K] = k_x \cdot k_y - k_{xy}^2$.

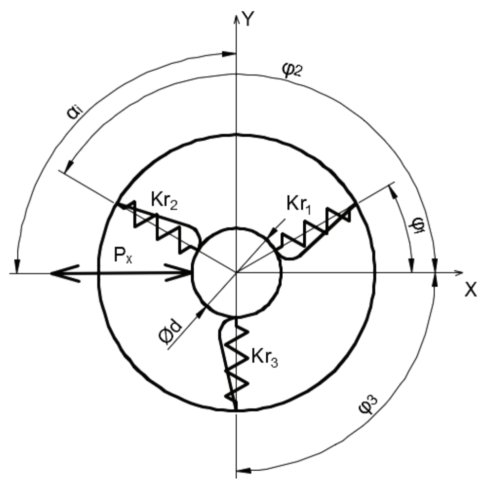

Fig. 6. Spatial position of the clamping elements and the load scheme

Then

$$D = \frac{1}{k_x \cdot k_y - k_{xy}^2} \cdot \begin{vmatrix} k_x & -k_{xy} \\ -k_{xy} & k_y \end{vmatrix}. \quad (9)$$

Consider a three-jaw collet for two positions corresponding to the load application on the *i*-th cam. When a load P_x is applied, the elastic displacement δ_x in the direction of the *OX* axis is determined by the correlation:

$$\delta_x = \frac{k_{y1}}{k_{x1} k_{y1} - k_{xy1}^2} \cdot P_x, \quad (10)$$

where

$$k_{x1} = k_{r1} \cdot \cos^2\varphi_1 + k_{r2} \cdot \cos^2\varphi_2 + k_{r3} \cdot \cos^2\varphi_3, \quad (11)$$

$$k_{y1} = k_{r1} \cdot \sin^2\varphi_1 + k_{r2} \cdot \sin^2\varphi_2 + k_{r3} \cdot \sin^2\varphi_3, \quad (12)$$

$$k_{xy} = k_{r1} \cdot \sin\varphi_1 \cos\varphi_1 + k_{r2} \cdot \sin\varphi_2 \cos\varphi_2 + k_{r3} \cdot \sin\varphi_3 \cos\varphi_3. \quad (13)$$

The system of equations (11)–(13) allows determining the angular hardness of individual cams in working condition based on the results of experimental measurements.

Under load, when the force is directed towards the workpiece:

$$\varphi_1 = 60°; \quad \varphi_2 = 110°; \quad \varphi_3 = -90°. \quad (14)$$

When the force is directed in the opposite direction:

$$\varphi_1 = 110°; \quad \varphi_2 = 60°; \quad \varphi_3 = 90°. \quad (15)$$

Computer processing of the experimental results with round chart plotting of radial hardness of the collet and its polynominal approximation were performed (Fig. 7). For a mathematical description of the form of deviations, interpolation of discrete values of ordinates by splines was performed. To do this, the built-in functions cspline and interp of the Math CAD package were used. Indicators of circular hardness in the form of functional dependence of circular hardness on the angle of rotation, load force and damping coefficient were defined experimentally (Fig. 7).

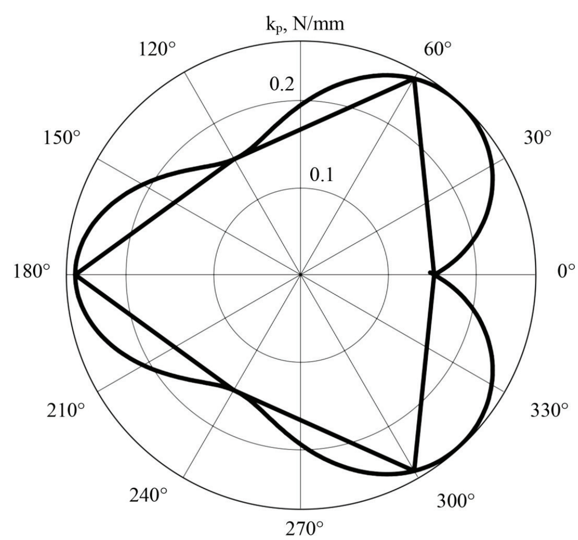

Fig. 7. Polar diagram of collet hardness in the polar system of polynominal approximation

6. Discussion of the results of the study of nonlinear hardness parameters of the collet-part system

When determining the deformation of the elastic collet-part system, nonlinear, elastic-dissipative processes take place in the contacts between the parts. This is due to the large number of contact pairs in the collet (15 or more), the presence of these processes leads to uncertainty (randomness) of the general characteristics of hardness. It should be noted that the presence of a large number of contact pairs in the collet leads to the fact that during wear of friction surfaces, the contact hardness is unstable in time.

As the friction surfaces wear out, their physical state changes. After separation of the next portion of wear particles, the surface becomes smoother and tougher. But with the accumulation of damage, it seems to be loosened, and the hardness drops again until the next separation of wear particles.

The obtained data of the effect of deformation of the elastic collet-part system make it possible to state the following:

– the results of the elastic pressing of the part in different angular positions are significantly different from the theoretical picture with an expressed three-lobe shape;

– on the other hand, the obtained results are in good agreement with the practical ones, as the typical error of machining a rigid part in a three-jaw collet is ovality.

Such uncertainty imposes restrictions on the use of the obtained results and can be interpreted as the shortcomings of this study. The impossibility to remove these limitations in the framework of this study gives rise to a potentially interesting line of further research. They can be focused on studies with the use of more sensitive digital equipment for recording pressing-out in the collet-part system.

This method allows measuring pressing-out in one angular position of the collet according to the loading pattern «on the cam» and «between the cams», which twice reduces the amount of experimental research. In addition, the technique takes into account the presence of random changes in the hardness parameters of the spindle and collet of a machine tool.

Detailed studies of elastic displacements in the collet-part system lead to the conclusion that the radially secured collets have fundamental flaws that should limit the use of such collets in the machining of high-precision parts.

7. Conclusions

1. The developed technique and equipment for experimental research on the basis of the analysis of the results of studies allowed investigating the peculiarities of the formation of nonlinear deformations of the collet-part component. The equipment includes a screw loading device, a circular two-way dynamometer, a mandrel fitted in the clamping chamber of the machine, and measuring devices in the form of indicators.

The ring dynamometer allows for two-way loading in the range from –1.200 N to 1.200 N with a discretion of 50 N at 24 points within a single load cycle. Recommendations on the estimation of stiffness change limits according to the structure of a cartridge are developed. The graphs of absolute displacements of the part in the cartridge look like typical loop-like hysteresis curves characteristic of mechanical systems with a large number of bonds.

2. For the collet-part system, the width of the hysteresis loop in the cold state can reach 20...70 microns. Hysteresis characteristics of the collet-part system – the part in the heated state has a hysteresis loop width of 50...200 μm with clamping of the part with a diameter of 80...115 mm and a radius of 100...120 mm.

3. The proposed technique allows measuring pressing in the one angular position of the collet according to the loading scheme «on the cam» and «between the cams», which doubles the amount of experimental research.

References

1. Orlikov M. L. Dinamika stankov. Kyiv: Vysshaya shkola, 1989. 272 p.
2. Litvin A. V. Technological systems lathe and its effects on processing nonrigid parts // Visnyk SevNTU. Seriya: Mashynopryladobuduvannia ta transport. 2014. Issue 151. P. 81–86.
3. Advancement of Intelligent Production. Chiba, 1994. doi: https://doi.org/10.1016/c2009-0-10316-1
4. Feng P. Berechnungsmodell zur Ermittlung von Spannkraeften bei Backenfuttern. Technische Universität Berlin, 2003.
5. A Study on Parametric Vibration in Chuck Work / Doi M., Masuko M., Ito Y., Tezuka A. // Bulletin of JSME. 1985. Vol. 28, Issue 245. P. 2774–2780. doi: https://doi.org/10.1299/jsme1958.28.2774
6. Lee J.-H., Lee S.-K. Chucking compliance compensation with a linear motor-driven tool system // The International Journal of Advanced Manufacturing Technology. 2004. Vol. 23, Issue 1-2. P. 102–109. doi: https://doi.org/10.1007/s00170-003-1696-9
7. Rahman M. A Study on the Deviation of Shape of a Turned Workpiece Clamped by Multiple Jaws // CIRP Annals. 1989. Vol. 38, Issue 1. P. 385–388. doi: https://doi.org/10.1016/s0007-8506(07)62729-2
8. Ema S., Marui E. Chucking Performance of a Wedge-Type Power Chuck // Journal of Engineering for Industry. 1994. Vol. 116, Issue 1. P. 70. doi: https://doi.org/10.1115/1.2901811
9. Byun J., Liu C. R. Methods for Improving Chucking Accuracy // Journal of Manufacturing Science and Engineering. 2012. Vol. 134, Issue 5. P. 051004. doi: https://doi.org/10.1115/1.4005947
10. Eggebrecht M., Georgiadis A., Wagner T. Strategies for correcting the workpiece deformation during the manufacturing at the milling process // Conferences 2013 – SENSOR 2013. 2013. P. 324–327. doi: http://doi.org/10.5162/sensor2013/B8.2
11. Modeling and simulation for the critical bending force of power chucks to guarantee high machining precision / Wang J., Zhang J., Feng P., Wu Z., Zhang G. // The International Journal of Advanced Manufacturing Technology. 2015. Vol. 79, Issue 5–8. P. 1081–1094. doi: https://doi.org/10.1007/s00170-015-6887-7
12. Contact mechanics applied to the machining of thin rings / Estrems M., Carrero-Blanco J., Cumbicus W. E., de Francisco O., Sánchez H. T. // Procedia Manufacturing. 2017. Vol. 13. P. 655–662. doi: https://doi.org/10.1016/j.promfg.2017.09.138