Evaluation of quality parameters of the torque transmission connections of the multi-purpose machine spindle joints

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Abstract. The article presents the results of theoretical studies of a multi-purpose machine when assembling an HSK spindle-mandrel connection for accuracy, contact stiffness and strength. Studies were based on the developed original mathematical program complex for assessing the quality parameters of machine connections. They have been carried out with respect to HSK spindle-mandrel connections under conditions of multiple tool changes. Simulation of the coupling of connection parts for different values of the fastening (assembly) forces showed that HSK-type connections have a static uncertainty of basing under external loading conditions. Analysis of the stress-strain state of the connection joints was based on the finite element method when using software in the FEMAP 11.1 with NX NASTRAN. It showed that an unorganized change of bases occurs under the influence of external conditional load. It has been established that for tool mandrels of the HSK-63 type with a fixing force of 900 to 23000 N, the elastic displacements at the end of the mandrel vary from 1.5 to 0.6 μm under the condition of an external conditional load of 1732 N and, accordingly, from 8.0 to 2.5 μm with an external load of 6070 N. It was established that with a limiting value of the mandrel clamping force equal to 23000 N under conditions of external loading an unorganized change of bases occurs, namely: the end faces of the contact of the tool mandrel and the spindle are pressed, which reduces the geometric accuracy of a multi-purpose machine with a CNC.

1. Introduction

Technological support for high-speed milling on CNC machines developed in [1, 2, 3], made it possible to create the basic prerequisites for the development of technology for manufacturing parts of round and profile connections of a conical shape of a longitudinal section of various standard sizes, while providing 6 accuracy classes for shaft type parts and 7 accuracy classes for sleeve parts.

In Russia, as well as in Germany and Japan, research is ongoing in the field of improving the design of technological equipment for multi-purpose CNC machines.

The work is aimed at developing fundamentally new and improving well-known designs of auxiliary tools working in conditions of reusable shift.

Currently, designs of tool mandrels of the SK, HSK, PSK type as well as BT and DBT taper shanks of 7:24 and 1:10 of a round cross-sectional shape and also of a profile cross-sectional shape in the form of an equiaxed contour with the number of faces equal to three for various fixing methods in the machine spindle [4, 5, 6, 7, 8, 9, 10].
The aim of this work is to assess the quality parameters of auxiliary tool designs of multi-purpose machines made on the basis of tapered connections of normal and special taper and operated under conditions of reusable assembly-disassembly of the spindle-mandrel connection.

Recently, studies have been carried out to assess the accuracy of the connection parts position when basing and fastening on the reproduction of the conjugation process with respect to conical connections of a round and profile cross-sectional shape with special and normal taper, taking into account the roughness of the connection parts (shaft), assembly force and other factors. The results of these studies are presented in the following [11, 12, 13].

To predict the accuracy, rigidity and strength of a spindle-mandrel conical connection, the accuracy of which is determined each time at the stage of its assembly and subsequent operation, a software-mathematical complex has been developed that made it possible to conduct a number of simulation experiments.

The statistical processing of the obtained results of machine experiments was carried out to determine the influence of the dominant factors, namely: the fixing force, conditional external loads, the slope angle of the cone, as well as the error in the shape of the connection parts on the accuracy of installation of the assembled parts of the conical connection under conditions of multiple replacement.

The application of the original computer-aided design technique developed in [14, 15, 16, 17, 18] and the analysis made it possible to establish that with an assembly force of 900 N a more accurate mutual position of the parts of the profile connection with an equiaxed contour with the number of faces equal to three with a taper of 1:10 is provided.

The calculations determined that the depressions (elastic displacements) of the profile mandrels are of the same order when compared with traditional round conical connections of the SK type.

At the same time, the former ones provide guaranteed immobility of the connection parts, and therefore exclude the change of bases during operation.

It is of interest to evaluate the accuracy, stiffness and strength parameters of HSK-type connections using well-known software systems.

2. Methods
The studies were carried out using the computer simulation technique developed in [12, 16] when constructing geometric models of module parts, namely: spindle-tool mandrel connections, methods of numerical solving problems of the theory of elasticity, including the finite element method (FEM), as well as the method of mathematical statistics and computer technology.

In [19, 20], the author developed mathematical models of the contact problem of deformable bodies intended for the analysis of prefabricated rotors using the modified variational-energetic method of displacements.

In this regard, it seems possible to analyze the stress-strain state of the prefabricated spindle assembly of the “spindle-tool mandrel” type of a multi-purpose machine using the method of numerical solution of FEM.

The elastic calculation of the FEM models of the prefabricated spindle assembly “spindle-tool mandrel” is based on the known dependences of the theory of elasticity and the principle of virtual displacements [16, 19], which leads to the well-known principle of stationarity of the potential energy of a mechanical system.

3. Results and discussion
The mandrels used in multi-purpose CNC machines of the HSK type are widely used in Germany and a number of European countries.

Currently, a standard has been developed providing, in particular, the basic requirements for the design of these mandrels of various sizes.

From studies conducted in Germany, as well as the results of the work of Russian scientists, the advantages of HSK mandrels in comparison with SK type tool mandrels are confirmed.
These advantages are known, it is the lowest weight of the mandrels due to the hollow cone of the mandrel; ensuring the immobility of the mandrel during rotation of the machine spindle by means of centrifugal forces of the collet clamping mechanism and, at the end, a more optimal option for installing the mandrel in the spindle, namely: centering of the mandrel and spindle flange along the truncated cone and the end surface in comparison with the method of installing mandrels of type SK on conical seating surfaces when fixing the magnitude of the force of consolidation.

The last advantage of an HSK-type mandrel is, namely: basing on four contact points is not entirely correct, since there are quite definite patterns for locating parts in engineering technology, such as: a double guide and two bearing bases; installation base, guide base and support base, according to the research of professor B.S. Balakshin.

We are talking about the deprivation of the joined part relative to another base part, the possibility of movements and turns in three directions, respectively, i.e. six freedom of movement.

From the foregoing it follows, that the HSK-type mandrel-based pattern can be defined either as a double guide along the surface of a truncated cone and two supporting bases, one of which is hidden (implicit) or, according to the basing scheme, an installation base along the end surface of the mandrel flange, a guiding base and support base.

The implementation of these basing schemes depends on the accuracy of manufacturing HSK mandrels and holes in the spindle, in particular: cone shape errors, slope angles, deviations from the perpendicularity of the mandrel flange with respect to the geometrical axis of the truncated mandrel cone (spindle cone).

Ensuring the last technical requirement is as follows: its non-observance due to the complexity of manufacturing technology leads ultimately to an unorganized change of bases in the case of repeated replacement of tool mandrels in multi-purpose CNC machines when replacing a cutting tool.

Solution of the problem by increasing the fixing force to 23000 N does not lead to certainty of basing, which follows from the results of the studies, namely: estimating of the installation error (basing and fixing) for different fixing forces under the condition of an external load (cutting forces).

Finite element calculations using software in the FEMAP 11.1 with NX NASTRAN based on finite elements in the form of eight nodal iso-parametric hexahedra (Figure 1) [19, 20] have been carried out.

![Figure 1. The finite element in the form of an iso-parametric hexahedron](image)

The necessary condition for continuity when using the finite element approximation is formulated according to [19, 20] in the following form: “the approximating function must be continuous together with its derivatives up to (n - 1) order inclusive; the presence of step-type discontinuities in derivatives of the n order is allowed, since the function under consideration remains bounded.
The fulfillment of this condition ensures the convergence of the numerical solution of the FEM while reducing the size of the finite elements.

Taking into account the continuity condition presented above, the sum of the changes in the potential energy of the acting loads $dW_p$ and the value of the internal strain energy $d\Lambda$, for a certain displacement field $\{\delta\}$, is zero [19, 20]:

$$d(\Lambda + W_p) = d\Pi = 0. \quad (1)$$

The work of acting external loads $W$ is equal in magnitude and opposite in sign to the work of internal forces, $W_p$ therefore it is equal to:

$$W_p = -W. \quad (2)$$

The energy state of the deformable mechanical system is characterized by the expression [19, 20]:

$$\Pi = \Lambda - W; \quad \frac{\partial \Pi}{\partial \{\delta\}} = 0, \quad (3)$$

where each of its components is a function of the displacement vector $\{\delta\}$.

According to the principle of stationarity of the quantity $\Pi$, to the displacement $\{\delta\}$:

$$\frac{\partial \Pi}{\partial \{\delta\}} = \sum_{e=1}^{E} \left( \int_{V^{(e)}} [B]^T [D][B] dV^{(e)} \{\delta\}^{(e)} - \{F\}^{(e)} \right) = 0, \quad (4)$$

where $E$ - is the number of elements into which the domain of definition is divided;

$V^{(e)}$ – is the volume of the finite element;

$[B]^T$ – is the transposed matrix of gradients;

$[D]$ – elasticity matrix;

$[B]$ – matrix of gradients (differentiation);

$\{\delta\}^{(e)}$ – is the vector of nodal displacements of the finite element;

$\{F\}^{(e)}$ – is the vector of the external equivalent nodal load of an individual finite element.

The integral in expression (5) determines the stiffness matrix of a single finite element:

$$[K]^e = \int_{V^{(e)}} [B]^T [D][B] dV. \quad (5)$$

Thus, the global stiffness matrix and the global column vector of equivalent nodal forces can be written as sums:

$$[K] = \sum_{e=1}^{E} [K]^e; \quad \{F\} = \sum_{e=1}^{E} \{F\}^e. \quad (6)$$

In matrix form which, make up the general equilibrium equation of the considered mechanical system:

$$[K]\{\delta\} = \{F\}. \quad (7)$$

The formation of the global stiffness matrix is carried out by summing from separate matrixes of elements (direct stiffness method) using topological information, which is a list of node numbers obtained from the global numbering of the finite element model of the object.

The formation of the force vector is carried out according to the nomenclature and topology of those areas of the finite element model where these loads are defined [21, 22].

As a result of solving the global system of algebraic equations (7), we have a certain displacement field represented at the nodal points by the values of the components of the global vector – the displacement column [21, 22].
The performed calculations show, firstly: the change in the elastic depressions (displacements) of the tool mandrels at different fixing forces of 900, 2300, 23000 N and external loading forces of 1732 and 6070 N are nonlinear (Figure 2, 3).

![Figure 2. Graphic dependence of the elastic squeezes of mandrels of the HSK type with external loading forces of 1732 N](image)

![Figure 3. Graphic dependence of the elastic depressions of HSK mandrels with external loading forces of 6070 N](image)

When carrying out calculations by the finite element method, the shape error of the mandrels and spindle was not taken into account, namely: macrogeometry and microgeometry of mating surfaces, as well as wear of mating surfaces.

As follows from the analysis of the calculation data, the smallest elastic depressions occur when the fixing force is 23000 N.
However, the analysis of the stress-strain state (SSS) (Figure 4, 5, 6, 7) shows that the basing scheme of the mating parts in the considered loading and fixing variants changes due to the depressions of the base surfaces of the mandrel and the spindle of the machine.

**Figure 4.** Fragment of SSS with a fixing force of 2300 N with an external load of 1732 N

**Figure 5.** Fragment of SSS with a fixing force of 23000 N with an external load of 1732 N
Figure 6. Fragment of SSS with a fixing force of 2300 N with an external load of 6070 N

Figure 7. Fragment of SSS with a fixing force of 23000 N with an external load of 6070 N
In both cases of external loading with forces equal to $F_0 = 1732$ N and $6070$ N, the mating base surfaces of the mandrel and the spindle of the machine break off even at maximum clamping forces (at $F_s = 23000$ N) of the first.

It confirms the fact of an unorganized change of bases due to the occurrence of lateral clearance at the joints of the mating parts of the spindle-mandrel connection, which significantly affects the geometric accuracy of the machine and the manufactured product.

4. Conclusions

1. It has been established that for tool mandrels of the HSK-63 type with a fixing force of 900 to 23000 N, the elastic displacements at the end of the mandrel vary from 1.5 to 0.6 microns with an external load of 1732 N.

2. It has been established that for tool mandrels of the HSK-63 type with a fixing force of 900 to 23000 N, the elastic displacements at the end of the mandrel vary from 8.0 up to 2.5 microns with an external load of 6070 N and are non-linear.

3. It has been established that at the limit value of the mandrel fixing force equal to 23000 N under conditions of external loading, an unorganized change of bases occurs, namely: the end faces of the contact of the tool mandrel and spindle are pressed out, which reduces the geometric accuracy of the CNC multi-purpose machine.

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