MODELLING AND CALCULATION OF MACHINE GEAR CUTTING TOOLS FOR DESIGNERS Monograph Prof. Marin Drinov Academic Publishing House of Bulgarian Academy of Sciences SOFIA 2021

Oleg Krol
East Ukraine Volodymyr Dahl National University

Oleg Krol

MODELLING AND CALCULATION OF MACHINE GEAR CUTTING TOOLS FOR DESIGNERS

Monograph

Prof. Marin Drinov Academic Publishing House of Bulgarian Academy of Sciences

SOFIA 2021

Reviewers:

Permyakov Oleksandr, Doctor of Sc., NTU “Kharkiv Polytechnic Institute”, Ukraine.
Nemtinov Vladimir, Doctor of Sc., Tambov State Technical University, Russia.
Tsankov Petko, PhD, Technical University of Sofia, Bulgaria.
Kovalevskyy Sergiy, Doctor of Sc., Donbass State Engineering Academy, Ukraine.

Oleg Krol
MODELLING AND CALCULATION OF MACHINE CUTTING TOOLS FOR DESIGNERS: monograph / Krol O. – Sofia: Prof. Marin Drinov Academic Publishing House of Bulgarian Academy of Sciences, 2021. – 150 p.: Table 9. Figure 71. Bibliogr. 103 names. English language.

The monograph deals with the design, calculation and modelling of gear cutting tools. Calculation forms are proposed for the creation of tools structures working by the methods of form-generating and form-copying. Three-dimensional and parametric models of worm wheel hob and worm spline cutters, shaper-type cutters and interlocking disk milling cutters in the environment of integrated CAD KOMPAS-3D and APM WinMachine using specialized applications “CAD Mills” have been built. Calculation forms for determining the geometric, kinematic and design parameters of worm wheel hob for the manufacture of spur and helical gears based on the original contour profile of a standardized gear rack are given. An interactive design of a worm wheel hob in the KOMPAS system was carried out. The design stage of determining the characteristics of the flank-shaped tooth profile modification to reduce the noise level and increase the service life of the gear transmission has been effectively implemented. An interactive procedure for designing a worm spline cutter in the KOMPAS environment for finishing spline shafts is proposed. At the stage of replacing the theoretical profile of the cutter tooth edge with an arc of one circle or tangent arcs of two circles, an express procedure for calculating the magnitude of the error is used. Computer design and research of the shaper-type cutter using the application program “Shaper cutter” in the KOMPAS-3D environment was performed. It is shown that for non-standard shaper-type cutters it is possible to use a standard helical copier of a gear shaping machine if the angle of teeth inclination is $15^0 \pm 0.5^0$ or $23^0 \pm 0.5^0$. A comprehensive study of interlocking disk milling cutters using the application program "Disk milling cutter" in the CAD KOMPAS contour was carried out. Parametric models of the disc cutter design are built using the syntax of the CAD APM WinMachine. The parametric models of a single- and double-relief tooth, as well as the involute profile of the tooth lateral surface, have been identified.

ISBN 978-619-245-145-5
DOI https://doi.org/10.7546/MCMGCTD.2021

Prof. Marin Drinov Academic Publishing House of Bulgarian Academy of Sciences
Acad. Georgi Bonchev Str., Bl. 6, 1113 Sofia, Bulgaria
www.baspress.com

INTRODUCTION

The development of modern modular systems of tools, representing a complex of various types of cutting and auxiliary tools, makes it possible to increase the versatility of tooling support, cover a wide range of problems in mechanical engineering technology, and solve important issues of implementing automatic tool change using tool magazines and manipulators (auto-operators).

Improving the accuracy of the executive dimensions, form and the relative position of the fastening and cutting elements is one of the main trends for tool production. Therefore, the values of the mutual run-out of the cutting blades of multi-blade tools decrease from 10-15 µm to 3-5 µm, and the AT4-AT5 classes instead of AT7-AT8 determine the accuracy of the shank base cones. The accuracy of multifaceted, non-grindable inserts in terms of the deviation of their edges from the ideal polyhedron does not exceed 1 µm, which ensures the preservation of the exact position of the cutting blade when replacing cutting edges or the tool itself.

The constructive design of the connecting points of the tools with the expansion of the use and development of machining centres makes it possible to ensure the possibility of their storage in permanent or replaceable tool magazines, moving with the help of an auto-operator into the machine spindle and automatic fixing in the spindle.

Modern tool production is distinguished by the widespread use of CNC machines and multi-axis machining centres, which allows not only increase productivity and accuracy but also implement several fundamentally new design solutions (for example, continuous specified measurement of clearance angles along the contour of cutting blades, etc.).

The use of such tool superhard materials (SHM) as artificial diamonds, cubic boron nitride, hexanit and others in the manufacture of tools affects all aspects of machining: accuracy, productivity and working conditions. Due to their high resistance and the ability to process materials of any hardness, these materials are especially suitable for automatic production conditions. In many cases, SHM blade tools instead of grinding tools, providing greater machining accuracy and less surface roughness are used.

The use of single- and multi-layer coatings applied to hard alloys and high-speed tool steels, in terms of efficiency can be attributed to new tool materials. These are very thin layers (2-12 μm) of carbides, nitrides and oxides of titanium, tantalum, niobium and other elements obtained by various methods (deposition from the gas phase, condensation with ion bombardment, etc.), increase the tool life by 2…10 or more times with minimal dimensional wear. These properties are most effectively used in conditions of automated production and high precision machining with dimensional tools.

One of the most complex and specific in terms of design, manufacture and operation is a Gear Cutter Tools (*GCT*). *GCT* intended for accurately formed cutting tools of hardened steel having shaped teeth that cut the space between the teeth of gear to the precise shape and size required. The creation of new projects in the field of gear processing should be solved comprehensively, taking into account its design features and purpose.

Gear wheels for cutting which the gear cutting tool is intended for are one of the most common parts in modern mechanical engineering and are used in various designs of machines and devices. Diverse areas of application, the general trend of increasing accuracy of mechanical engineering objects, increasing peripheral speeds, and high power transmission leads to increasing demands on gear drives, and this, in turn, to methods of processing gears and GCT [1-3]. The GCT-characteristics affect the formation of the correct tooth shape, which in turn determines the quality of the gear transmission concerning the smoothness and accuracy of the contact between the teeth.

The types of gears used in mechanical engineering, in turn, predetermine the variety of GCT-types and design features.

There are the following types of rotational movement, distinguished by the mutual arrangement of the shaft axes: spur gears with a parallel arrangement of the shaft axes; bevel wheels with intersecting shaft axes; worm and spiroid gears with crossed shaft axes.

In turn, transmissions by spur gears are divided into transmissions with involute, circular screw (Novikov's transmission), cycloid gearing.

Transmission by bevel gears according to the location of the tooth is divided into spur, helical and curved teeth, and in shape, they can be involute, rectilinear, and cycloid.

Worm gears are divided into two types – cylindrical and globoid. In turn, cylindrical worms have several varieties – convolute, Archimedean, involute.

Gear wheels and spline shafts can be processed by two methods – form-coping and form-generating [4–6].

The form-coping method consists of simultaneous rolling without sliding of the tool centroid and the gear wheel being cut, while the profile of the cut product is obtained in the process of machining as an envelope of various positions of the tool cutting edges. These tools include hob cutters, shapers, rack-type gear, gear cutting heads, etc.

The form-generating method is a progressive method for machining gears in terms of performance and accuracy. This method provides cutting of gears in the range of modules 0.1...40 mm with an accuracy within 5...11 grades and is used in individual, serial and mass production.

The copying method has a narrower field of application: individual (end-mill and disc milling cutters) and serial production of gear wheels of 9...12 quality class (tolerance grade). The method of copying has found the greatest application in the processing of large-module gear wheels (module over 20 mm) when the use and manufacture of tools obtained by the form-generating method are difficult.

The process of mechanical engineering products release begins with the design of the future product. Designing products to meet the demands of a rapidly changing market enables enterprises to grow and become successful. The release of new competitive products provides a profit.

For effective design, you can use one or more integrated CAD systems. One of the dynamically developing CAD/CAM/CAE systems is the KOMPAS-3D system developed by the ASCON group of companies [7-9]. The solutions offered by ASCON for mechanical engineering automate the processes of design and technological preparation of production. Application of ASCON software products together with methods of their use, experience and know-how of enterprise specialists reduce the development time for new products, reduce the cost price and improve the quality of manufactured products.

KOMPAS-3D allows you to create a full-fledged model of a future product, using, among other things, a set of full-featured specialized applications [10, 11].

Using the “Shafts and mechanical transmissions-3D” application, the following elements of mechanical transmissions can be designed: spur gears; bevel gears with straight and circular teeth; worm shaft and worm wheels. At the same time, design calculations allow you to select several gear options that meet the specified operating conditions.

In addition, a specialized program for the basic application “Shafts and mechanical transmissions-3D” is intended for designing gear cutting tools [12-15].

These are primarily Wormwheel Hob (WH) cutters, which are the most common gear cutting tools, used for rough and fine gear cutting. The program will allow you to calculate and build models of WH for cutting:

- spur gears with an involute profile (roughing and finishing cutters);
- Novikov's gears with two lines of engagement;

- sprocket-wheels to drive roller and bushing chains, worm wheels of a cylindrical worm gear (roughing and finishing milling cutters);

- splined shafts with an involute profile, splined shafts with a straight flank profile.

The result of work in the basic application is a fully completed drawing for the cutter (with external elements and a table of parameters) and its 3D model.

It provides for the development of design documentation for standard milling cutters (according to domestic standards) and the design of milling cutters for gear wheels and spline shafts (according to foreign standards). For wheels with an involute profile, milling cutters with a non-standard module or basic contour are available.

The gearing or spline shaft data for the worm hob is taken from the calculation form or databases of the “Shafts and mechanical transmissions-3D” application. Wormwheel Hob is a fluted rotary cutter used to produce spur, helical and worm gear, a worm-shaped cutting tool having some flutes or gashes running across the thread so that a series of cutting edges is formed.

The gear part of the cutter is a complete component of the 2D model of the application. This implementation allows you to create not only standard milling cutters for a cylindrical mandrel but also to combine the gear cutting part of the cutter with special shanks designed for certain gear cutting machines.

The features of the application program include:

- allows you to design any cutters – just get a drawing of the product or information on which foreign standard to make a tool.

- high design speed. Typically, a qualified engineer spends two days calculating and documenting standard WH. The application allows you to reduce the development time to a few minutes.

- generates 3D models of tools.

1. WORMWHEEL HOBS DESIGNING USING THE KOMPAS-3D SYSTEM

Worm hobs for cutting spur gears are used for rough, semi-finishing and finishing cutting of spur and helical gears of 0.1 ... 40 mm modules (Fig. 1.1). According to GOST 9324-80 E, depending on the purpose and size, worm cutters are manufactured with accuracy classes AAA, AA, A, B, C, D and are recommended, respectively, for cutting gears 5-6, 7, 8, 9 and 11-th degree of accuracy. The labour intensity of gear hobbing for wheels m = I0 ... 20 mm is 15 ... 10% less than the labour intensity of gear shaping. In addition, the same milling cutter can cut both spur and helical gears. The shape of the teeth profile of the cutters depends on the shape of the teeth profile of the cut wheels – involute, cycloid, etc., which designing, should be set by the profile of the basic contour of the gear rack [16-18].

The WH is divided into arbor-type and shank-type milling cutters, right-handed and left-handed, single-and multi-thread, solid, composite and interlocking. Worm cutters work on special gear cutting machines of models 5K30I, 5K320, 5K32, 5342, 5445, 5364, etc.

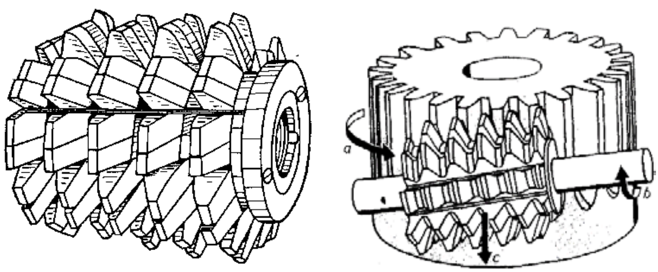


Fig. 1.1. Worm hob cutter: a – design; b – cutting scheme

1.1. Calculation of the cut gear wheel

In the process of performing the work, the WH is calculated when cutting by the method of form-generating in a spur gear wheel (Fig. 1.1). The profile of such a wheel is formed by two symmetric engagement involutes, the parameters of which are regulated by the GOST 13755-81 standards. GOST 16530-83; GOST 16531-83 and GOST 16832-70.

At the initial stage of the WH calculating, the main geometric parameters of the gears being cut and conjugated with it are determined under the schematic diagram by GOST 16532-70.

The dimensions of the tooth basic contour (BC) of the gear rack determine the main parameters of the gears teeth. GOST 13755-81. Similarly, the dimensions of the gear cutting tool teeth are characterized by the parameters of the basic producing contour (BPC) of the tool rack, which is the basis for the design of this tool (Fig. 1.2) [19-21].

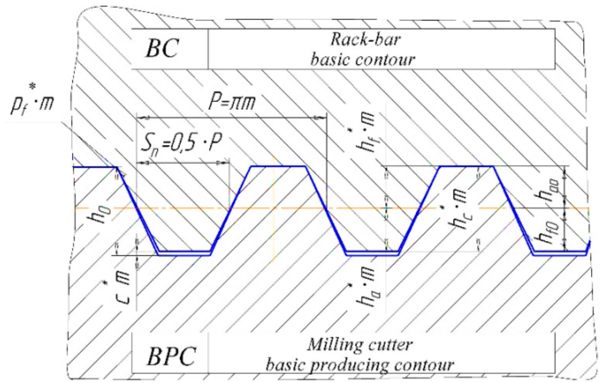


Fig. 1.2. Basic contours

The initial data at the first stage are (Table 2.1):

m – module of engagement, mm;

z_1, z_2 – teeth number of the cut and conjugated gears;

β – inclination angle of the screw teeth, degrees;

x_1 and x_2 – coefficient of displacement of the cut and conjugated wheels;
α – angle of the main profile of the basic contour of the cut wheel, degrees. For a normal, nominal basic contour, angle $\alpha = 20^0$;
h_a^* – coefficient of the head height for the rack tooth;
c^* – coefficient of radial clearance;
h_g^* – coefficient of the head modification height;
Δ^* – coefficient of the head modification depth.

Two possible options of calculation algorithms should be noted:
- at a given centre distance a_w;
- at the given displacement coefficients x_1 and x_2 (if the value a_w is not specified).

With the basic contour following GOST 13756-81, the values x_1 and x_2 are recommended to be selected taking into account Appendices 2 and 3 of GOST 16532-70.

The calculation of the main geometrical parameters of gears is carried out following GOST 16532-70 in the following sequence.

1. Center distance calculation a_w:

$$a_{\text{w}} = \frac{(z_1 + z_2)m}{2\cos\beta} \cdot \frac{cos\alpha_t}{\cos\alpha_{tw}},$$

where a_t – profile angle in the end section;

$$tg\alpha_t = \frac{tg\alpha}{\cos\beta}$$

α_{tw} – involute angle (involute angle of the tooth profile):

$$inv_{tw} = \frac{2x_\Sigma tg\alpha}{z_1 + z_2} + inv\alpha_t,$$

where $x_\Sigma = x_1 + x_2$ – coefficient of the sum of the displacements.

2. Calculation of the pitch diameter of the gear (d_1) and wheel (d_2):

$$d_1 = z_1 \cdot m / \cos\beta; \quad d_2 = z_2 \cdot m / \cos\beta .$$

3. Gear ratio calculation *u*:

$$u = z_2 / z_1 .$$

4. Calculation of pitch diameters d_{w1} and d_{w2}:

$$d_{w1} = \frac{2a_w}{u+1}; \quad d_{w2} = \frac{2a_w \cdot u}{u+1} .$$

5. Calculation of the perceived displacement coefficient y (GOST 16531-83):

$$y = \frac{a_w - a}{m} ,$$

where *a* – pitch centre distance;

$$a = (z_1 + z_2)m / 2\cos\beta .$$

6. Calculation of the coefficient of the equalizing displacement Δy:

$$\Delta y = x_\Sigma - y .$$

7. Calculation of the diameters of the teeth tips d_{a1} and d_{a2}:

$$d_{a1} = d_1 + 2\left(h_a^* + x_1 - \Delta y\right)m ;$$

$$d_{a2} = d_2 + 2\left(h_a^* + x_2 - \Delta y\right)m .$$

8. Calculation of the dedendum diameters d_{f1} and d_{f2}

$$d_{f1} = d_1 - 2\left(h^*{}_a + c^* - x_1\right)m$$

$$d_{f2} = d_2 - 2\left(h^*{}_a + c^* - x_2\right)m .$$

9. Calculation of the tooth thickness S_n in the normal section:

$$S_n = \left(\frac{\pi}{2} + 2xtg\alpha\right)m ,$$

where *x* – displacement factor; $S_n = S_{n1}$; $x = x_1$ – for the grooved wheel.

The calculation of the basic geometric parameters is simplified in the following cases: spur gears $(\beta = 0)$, are designed $a = 0.5 \cdot (z_1 + z_2)m$; $\alpha_t = \alpha$; $d = zm$, when the center-to-center distance a in the normal section is equal to the center-to-center distance measured along the initial surfaces, i.e. $a = a_w$, in this case we obtain $\alpha_{wt} = \alpha_t$; $x_\Sigma = 0$; $d_w = d$; $y = 0$; and $\Delta y = 0$.

The above geometrical parameters (p. 1. – p. 9) are a fragment of the calculation following GOST 16532-70 and for the first step of interactive design in the KOMPAS environment (the "Gearwheel parameters" window) are used.

In this window, you should enter, by the specified option, the following data:

1. The module of the cut wheel – m_1.
2. The direction of the tooth line (left, right, straight).
3. The angle of the basic contour profile – α.
4. The thickness of the wheel tooth S_{n1} – (calculation).
5. Tooth addendum diameter – d_{a1} (calculation).
6. Pitch diameter – d_1 (calculation).
7. Dedendum diameter – d_{f1}, d_{f1} (calculation).

After completing the input, click the "Apply" button.

Pay attention to the use of various controls of the KOMPAS system dialogue.

Counter 

– allows you to set the desired numerical value (in the first window, this refers to the module *m* and the angle α).

Switch  – allows you to select one of several options; united in a group ("Tooth line direction").

1.2. Calculation of the wormwheel hob

After receiving the design data for the spur gear to be cut, a phased interactive design of a WH is carried out in the KOMPAS system [22-24].

The methodology and calculation considered below are focused on single-cut WH for spur gears with an involute profile following GOST 9324-80.

The initial data for the calculation are:

The degree of precision of the cut wheel. Table 1.1 shows the values of the accuracy degree for the cut wheel following GOST 1643-81 and the corresponding classes of cutter accuracy. For this calculations variant, wheels of the 6th degree of accuracy will be considered.

Table 1.1

Assignment of the WH accuracy class according to the accuracy degree of the gear being machined

Name of the cutter	The accuracy degree of the wheel (GOST 1643-81)	Accuracy Class of the cutter
Single-thread WH precision, *m* = 1…10 mm	6	AAA
	7	AA
single-thread WH precision for general purpose, *m*= 1…20 mm	8	A
	9	B
	10	C

Milling cutter type – Type 1. This calculation considers type 1 solid precision milling cutters with modulus values from 1.0 to 10 mm.

Cutter embodiment – normal length.

Accuracy class – AAA or AA with modification.

Modification type – flank.

The number of the cutter threads, n_{Z0} = 1 – single-thread cutter.

Radial clearance ratio c^*: c^* = 0.25.

The amount of allowance for shaving h_{sh} – according to Table 1.2 [24].

Table 1.2

Thickness tooth allowances for shaving

Module *m*, mm	1	2	3	4	5	6	7	8
Allowance h_{sh}, мм	0.05	0.06	0.07	0.08	0.09	0.1	0.11	0.12

The allowance for the thickness of the tooth δ_{gr} for the subsequent processing of the wheel by grinding is determined by the following relationship:

$$\delta_{gr} = 0.5\sqrt[3]{m} \cdot tga$$

The characteristics listed above, by the specified option (Table 1.1), are entered into the "Initial data of the cutter" window using the "counter", "switch" and "flag" controls. The last element is used to set or cancel the operating mode (set or cancel an option).

At the second stage of calculating the hob cutter, the type of modification is established. In this guideline, a modification of the flanking type for cutters with a modulus of more than 2 mm by checking the appropriate checkbox in the KOMPAS window "Modification of a profile for shaving" is selected. Modification of the involute profile allows reducing the noise level and increasing the service life of the gear train, as well as compensating for deformations during heat treatment.

In the same window, the angle of inclination of the tooth line is specified (from the table of initial data). For helical gears, the value β is taken from the range: β = 8…15^0; with an increase β > 20^0; for cutters, an intake cone is made at an angle $\varphi_{\kappa_0} = 7 \div 10^0$ along the length $l_{k_0} = (5 \div 7)m_0$.

At the third stage of the calculation in the window "Profile of teeth in the normal section", the analysis of the basic dimensions of the basic contour is carried out. It is possible to adjust the radius of the root ρ_f and head ρ_a of the tooth.

The radii of curvature at the tip (head) ρ_{ao} and root (foot) ρ_{f0} of the cutter tooth can be determined by the following ratios:

$$\rho_{ao} = (0.25...0.3)m;$$
$$\rho_{f0} = (0.2...0.3)m.$$

After these steps, click the "Apply" button.

At the fourth stage, in the window “Calculation of the cutter flank”, the flank angle is entered (more precisely, the total value of the profile angle and the flank angle). It is possible to adjust the modification height h_g (after placing the cursor in the corresponding input field).

When you enter the height of the flank on the gear tooth head, the flank width and the diameter of the modification circle of the gear teeth heads (passing through the starting points of the modification line) are automatically changed.

Like the teeth of gears, the dimensions of the teeth of a gear cutting tool are characterized by the parameters of the basic generating contour (BGC) for the tool rack, which is the basis for the design of this tool (Figure 1.2).

Flank parameters for a normal nominal basic contour following GOST 9324-80 are selected. The height h_{f0} and depth a_{f0} of the flank depending on the module are selected. Approximate ratios also apply:

$$h_{f0} = (0.45 \div 0.5)\ \text{m};$$

$$a_{f0} = (0.005 \div 0.02)\ \text{m};$$

$$\alpha_{f0} \le 5^0 .$$

At the fifth stage in the window “Tooth angles”, you can change the values of the back clearance angle of the cutter. Tip back clearance α_{tp} = α_{a0} set within 10…12^0.

The back clearance angle at the lateral cutting edge α_{l0} in the section perpendicular to it is determined by the formula:

$$tg\alpha_{lO} = \frac{r_{ao}}{r_x}\, tg\alpha_{ao} \sin\alpha_{xo},$$

where r_x – circle radius of an arbitrary point location for which the angle α_{lO} is considered. The value shouldn't be less 3^0. The "Tooth angles" window contains the value of the back clearance angle α_{lO} the value of which depends on the entered angle α_{a0} (it changes automatically when a new value is entered α_{a0}).

The front rake angle at the tip of the tooth $\gamma_{tp} = \gamma_{ao}$ is taken to be zero.

At the sixth stage, the following parameters should be set in the "Main structural dimensions" window (in case of specifying non-standard structural parameters):

d_{a0} – diameter of the teeth tips;

d – mounting bore diameter.

In this window, to enter numerical values d_{a0} and d a counter is used.

Diameters d_{a0} and d for finishing single-thread WH following GOST 9324-80 are selected. For the diameter of the mounting bore *d*, there is an approximate relationship:

$$d \le 0.625(d_{ao} - 2h_{gr}),$$

where h_{gr} – depth of the chip groove, determined according to the reference book [4].

Groove depth for cutters with a grinding profile:

$$h_{gr} = h_0 + \frac{k + k_1}{2} + (1 \div 1.5);$$

for cutters with non-grinding profile:

$$h_{gr} = h_0 + k + 0.5.$$

In the next window "Tooth geometry" the following parameters are set:

1. The amount of backing-off relieving of the tooth *k*;
2. The amount of double backing-off relief k_1;
3. Height of the cutter tooth h_0;

The following formulas to calculate these parameters are used:

$$k = \frac{\pi d_{a0}}{z_0} tg\alpha_{ao};$$

$$k_1 = (1.2 \div 1.5)k;$$

$$h_0 = 2.5m,$$

values *k* and k_1 rounded up or down to 0.5.

The values *k* and h_0 are selected from GOST 9324-80. Backing-off relieving ensures that the actual tooth profile remains constant when regrinding along with the rake. The necessary information about the relief process in the appendix is given.

The angle of the groove α_{gr} profile is taken equal to 25^0 or 30^0, and the radius of curvature of the groove root ρ_{gr} can be calculated from the following relationship:

$$\rho_{gr} = \frac{\pi(d_{a0} - 2h_k)}{10z_0}.$$

In addition, in the window under consideration, it is possible to change the angle of the groove profile α_{gr} and the radius of curvature of the groove root ρ_{gr}.

After entering the above data, the system performs a check calculation and estimates the dimensions of the dangerous section. To do this, it is necessary to estimate the thickness T between the bottom of the chip groove and the keyway of the cutter from the strength condition. This condition is satisfied if:

$$T = r_{ao} - (c_1 - r + h_{gr}) \geq 0.25d,$$

where r_{ao} – radius of the teeth tips;

c_1 – the size of the keyway (GOST 9472-85);

r – radius of the mounting bore.

In the case of an insufficient value of the dangerous section in the KOMPAS system, three correction options are proposed:

1. The inclination angle of the grooves ω to take 0. Such grooves are parallel to the axis of the cutter and the straight are called. This makes sharpening the teeth much easier. However, the rake angles for the left and right cutting edges of the cutter will be different. Therefore, cutters with straight grooves are made with small lifting angles of the turns.

$$\tau_0(\gamma_{mo}) = 3 - 5^0.$$

2. Reduce the mounting bore diameter d.

When decreasing the value *d*, use the value from the normal range of the hole diameters of the arbor-type tool (GOST 9472-83). For cutters of the same type, this range includes d = 32, 40, 50, 60 mm.

3. Change the parameters.

After the correction procedure, the parameters of the keyway are selected according to GOST 9472 – 83.

At the final stage, a dialogue procedure is carried out in the "Design parameters" window. Here you can analyze parameters such as cutter length L, bead length and bead diameter d_1

There are recommendations for the size of the beads. The surface of the beads is made strictly concentric with the turns of the main worm passing through the cutting edges of the cutter and are used to control the absence of run-out of the cutter when mounted on a gear cutting machine. The length of the beads $l = 3 \div 5$ mm and the diameter of the beads d_1 is 1…2 mm less than the circle passing through the bottom of the cutter groove. For the finishing WH values, l and d are normalized by GOST 9324 - 80.

The milling cutter length L must ensure the correct profiling of the teeth. Calculations show that the total length of the cutter: $L = 0.8\ d_{a0}$. When assigning the length, the addition of one or two axial steps is taken into account for the displacement of the cutter in the process of teeth wear and for cutting off the ends of incomplete turns. Type 1 standard cutters are available in lengths from 71 to 180 mm.

In the same window, you can change the length of the grinding part of the mounting bore from each end, as well as the diameter of the bead and the dimensions of the keyway.

1.3. Technical requirements

Under technical requirements (GOST 9324-80):

1) solid cutters and gear racks for interlocking cutters must be made of high-speed steel (GOST 19265-73) with the hardness of the working part 63 ... 66 HRC_e;

2) grinding part must be at least 1/2 of the tooth length for *m* = 0.15 ... 4 mm and 1/3 of the tooth length for *m* > 4 mm;

3) incomplete turns should be dulling so that the thickness of the upper part of the tooth along its entire length is at least 0.5 *m*;

4) parameters of the surfaces roughness of the cutters should be no more than the values indicated in Table. 4.1 [4];

5) tolerances and maximum deviations of the checked parameters of the cutters should not exceed the values indicated in the Table. 4.2 [4];

6) maximum deviations for the addendum diameter, the diameter of the beads and the total length – h16;

7) on the end face of the cutter must be written: the trademark of the manufacturer, the module, the angle of the turn, the pitch of the helical chip groove, the letter *L* on the left-thread cutters, the grade of the tool material, the year of manufacture.

1.4. Design in the KOMPAS-3D environment

As an example, let us consider a single-thread Wormwheel Hob (WH) for spur gears with an involute profile of type 1 [25-27]. This milling cutter belongs to one-piece cutters of modules 1 ... 10, accuracy class AAA and AA, made of high-speed steel.

The WH design process is broken down into a number of stages.

Stage 1 - calculation of the gear to be cut. Let's take as initial data:

- module $m = 5$;
- number of teeth of the cut wheel $z_1 = 33$;
- number of teeth of the conjugated wheel $z_2 = 42$;
- inclination angle of the helical teeth $\beta = 0$;
- displacement coefficient of the cut and conjugated wheels $x_1 = 0$, $x_2 = 0$;
- angle of the main profile of the cut wheel basic contour $\alpha = 20^0$
- standardized coefficients: $h_a^* = 1$; $c^* = 0.25$; $h_g^* = 0.45$; $\Delta^* = 0.02$.

As a result of using the standard technique, we obtain the main geometric parameters of the cut wheel:

$$d_1 = 165\text{ mm};\ d_{w1} = 165\text{ mm};\ d_{a1} = 175\text{ mm};\ d_{f1} = 152.5\text{ mm};$$

$$S_n = 7.854\text{ mm}.$$

Stage 2 – further calculation and design of the WH are performed using the application library included in the KOMPAS software package.

The KOMPAS program is called in a standard way. After that, the application libraries are connected by clicking the icon of the library manager. In the menu that appears (Fig. 1.3), you need to open the "Equipment, tools" folder and select by double-clicking "CAD MILLING CUTTER 1.25" (CAD MC) [28-30].

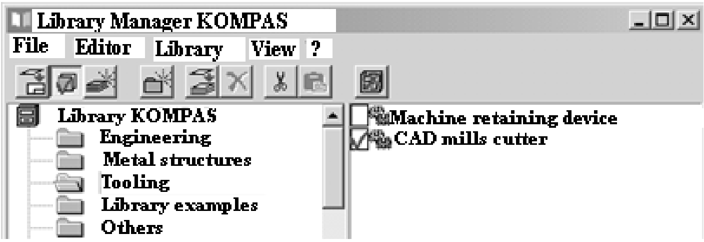


Fig. 1.3. Application libraries of KOMPAS-3D

Immediately after the program run, the main application window appears on the screen (Fig. 1.4). It is divided into two fields containing the main menu and the toolbar.

The main menu of the system is the standard control of the system operation. To speed up the work, some menu items on the toolbar are duplicated. Menu items using the mouse or keyboard are selected.

The toolbar for quick access to commands is used. Each button on the toolbar corresponds to one of the main menu items.

From the main menu, select *Options*/WH.

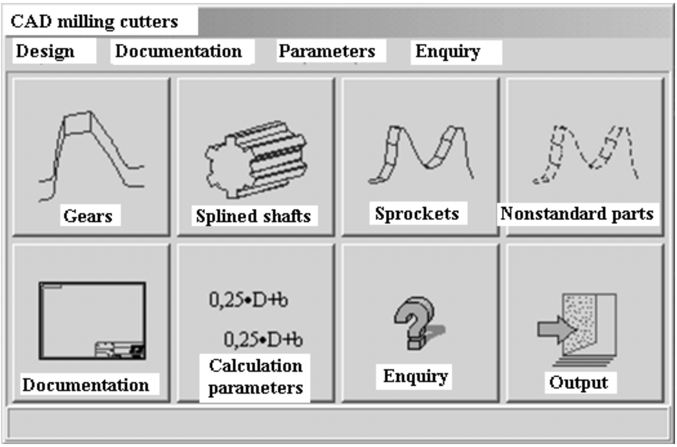


Fig. 1.4. Application Library Main Menu of CAD MC

To continue the calculations, you must specify the location on the disk where the results file will be written. At the request of the system, specify your folder Z:/Petrov and type the name of the results file (for this example, Test_000). Click the *Save* button.

In the "Gearwheel parameters" window (Fig. 1.5) set the following parameters:

- module – 5 mm;
- angle of the tooth profile of the basic contour – 20^0;
- wheel tooth thickness – 7.85 mm;
- addendum (top) diameter– 175 mm;
- pitch diameter – 165 mm;
- dedendum (root) diameter – 152.5 mm;
- direction of the tooth line – right.

Click the "Apply" button.

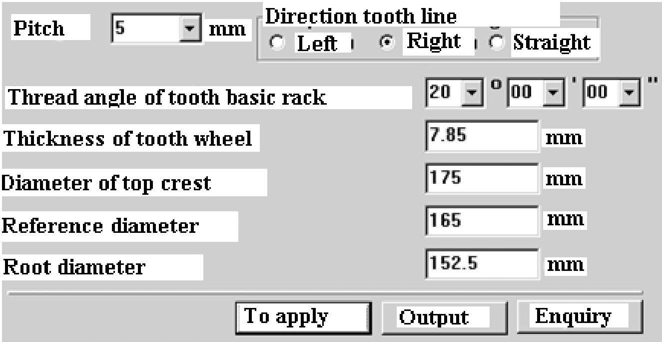


Fig. 1.5. Gear options window

In the window "Initial data of the wormwheel hob" (Fig. 1.6) set the following parameters:

- wormwheel hob – finishing;
- WH type – 1;
-embodiment – normal length (not activated);
- accuracy class – AAA, with modification;
- allowance size – 0.09 mm;
- number of WH threads (starts) – 1;
- radial clearance factor – 0.25.

Click the "Apply" button

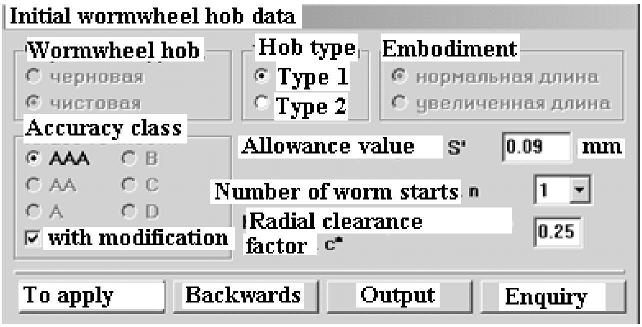


Fig. 1.6. Cutter Initial Data Window

In the "Modifications of the profile for shaving" window (Fig. 1.7), check the box for the "Flanks" option [31] and enter the value of the angle β = 0 and click the "Apply" button.

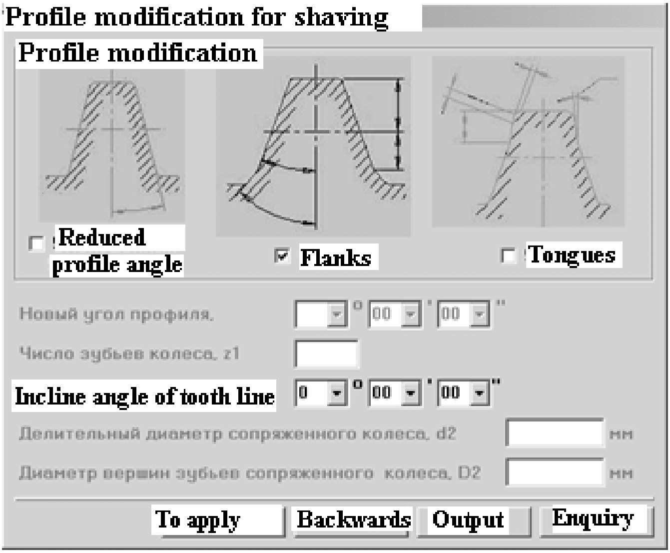


Fig. 1.7. Window "Profile modification for shaving"

In the window "Profile of teeth in the normal section" (Fig. 1.8), the main parameters of the profile are displayed [32]. This window contains information about the parameters of the contour with the ability to change the radius of rounding of the root and head of the teeth, taking into account the requirements of GOST 9324-80.

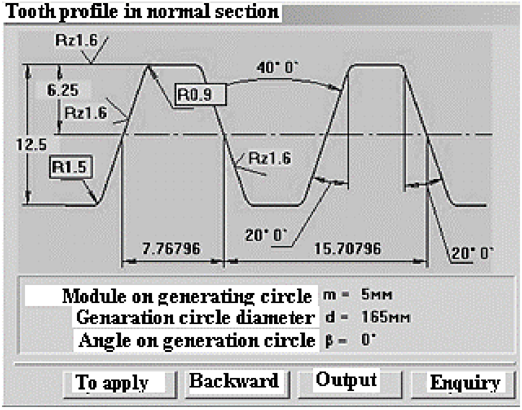


Fig. 1.8. Normal Section Tooth Profile Window

In the window "Calculate the flank of the cutter" (Fig. 1.9) change the angle of the flank and enter the value 25^0. Pay attention to the value of the height and depth of modification. With an increase in the flank angle of more than 5^0 (standard 25^0), the ratio of h_g and Δ changes, while the value Δ exceeds the limiting values (GOST 13755-81).

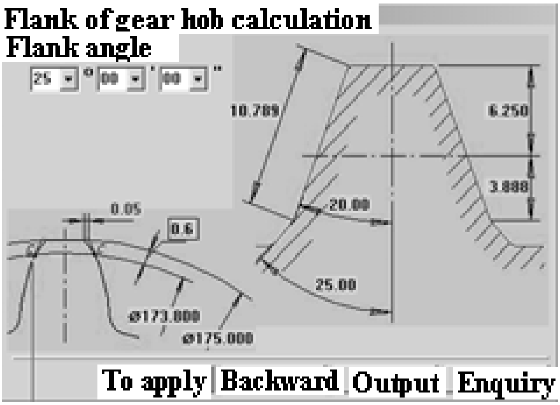


Fig. 1.9. Gear hob flank calculation window

In the window "Angles of teeth" (Fig. 1.10) leave the angle $\alpha_{tp} = \alpha_{a0} = 10^0$. unchanged, provided that $\alpha_{lo} \geq 3^0$.

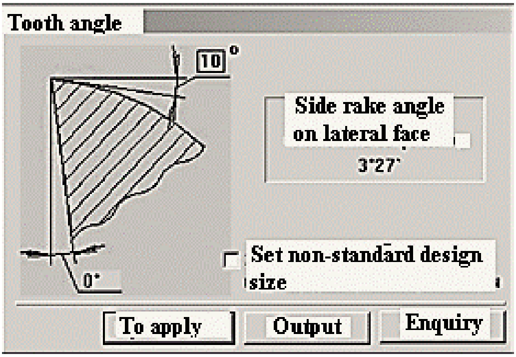


Fig. 1.10. Tooth angles window

In the window "Geometry of teeth" (Fig. 1.11) check the values of the relief, if necessary, enter the standard values.

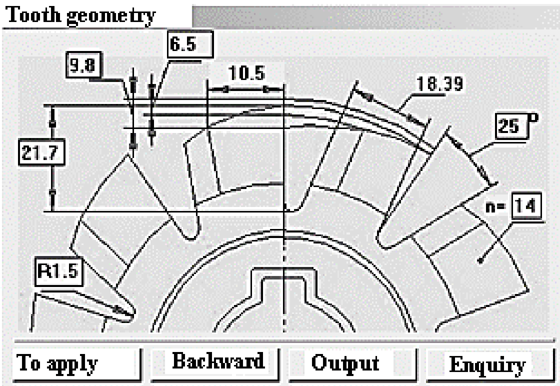


Fig. 1.11. Tooth geometry window

In the "Key slot" window (Fig. 1.12), check the suggested values and, if necessary, change their values.

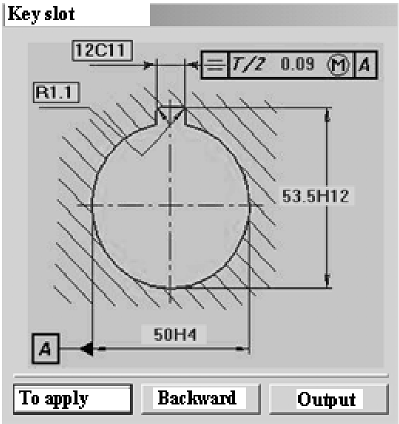


Fig. 1.12. Key slot window

In the "Structural dimensions" window (Fig. 1.13) set the following parameters:

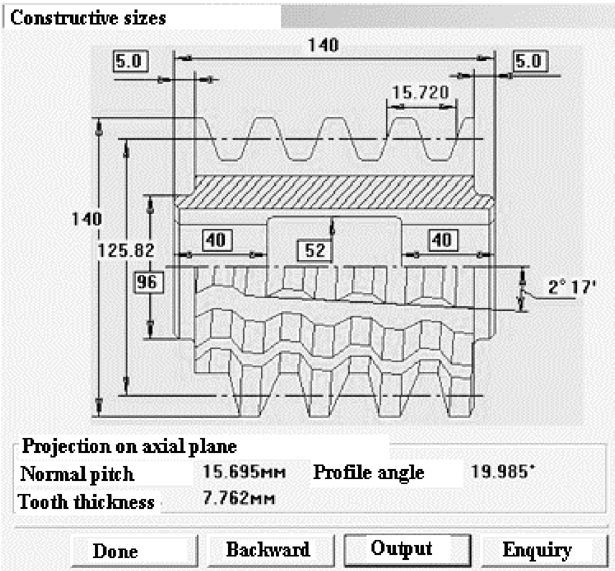


Fig. 1.13. "Structural dimensions" window

When prompted for the number of the cutter, enter the number 00001 or the text coding of the cutter. Click the "Apply" button.

Obtaining documentation:

- From the main menu, select *Documentation*/*Create Documentation*.
- At the request of the system, select the Z:/Petrov directory and select the Test_001.rzl results file.
- Click the "Open" button. Wait, after creating the documentation, the system will display the message "Documentation has been created". The results of calculating the WH profile are presented in Appendix A1.

2. WORM SPLINE CUTTER DESIGNING USING THE KOMPAS-3D SYSTEM

Worm Spline Cutters (WSC) are used for processing spline shafts by the form-generating method [33-35]. Spline connection refers to the connection of two parts with evenly spaced slots and horns (movable and fixed in the axial direction).

The advantages of spline joints include:

a) effective centring of parts and improved direction when moving the shaft;

b) reduced shear stress on the edges of the splines in comparison with keyed connections;

c) increased strength of spline shafts at alternating stresses.

The most widespread are rectangular (straight-sided) and involute spline joints.

Following GOST 1139-80 general-purpose spline joints with straight-sided tooth profiles are divided into light, medium and heavy series connections. In turn, splined shafts have three types of embodiments A, B and C. Versions A and C are used when centring on the inner diameter, and version B – when centring on the outer diameter (Fig. 2.1).

The essence of centring according to one of the shaft parameters is that, depending on its type, the size is set more accurately only for one of them, while the other is performed with less accuracy.

For centring dimensions following GOST 1139-86, various tolerance fields are used from *g*5 to *d*10, and for non-centering diameters – *d*11 (outer diameter of the shaft). So, for a WH accuracy class *A*, when centering on the inner diameter *d*, the tolerance field *e*8 is preferable.

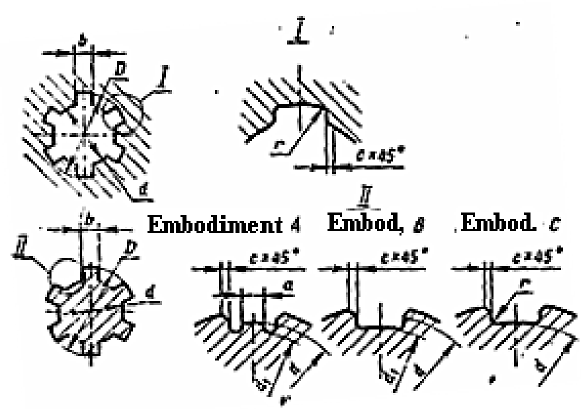


Fig 2.1. Splined joints with a straight-sided profile of teeth

For processing products with a straight profile, the most common are WSC made of tool high-speed steels, in which the chip grooves are milled and the teeth are backing-off relieved. The WSC can be thought of as consisting of several rack bars evenly spaced around the circumference, and each of them is offset in the axial direction (Fig. 2.2). WSC following GOST 8027-86 are divided into two types (according to the type of centering) and must be made right-handed with a left-hand direction of helical chip grooves. There are three classes of accuracy *A*, *B* and *C*. WSC of classes A and B are intended for fine cutting of shafts, and accuracy class *C* for roughing.

Shafts are machined on spline shaft milling machines. The axis of the WSC is crossed with the axis of the workpiece, and the direction of the threads coincides with the splines of the shaft. The tool and the product are given a cinematically coordinated rotation about their axes. In one turn of the cutter, the shaft will rotate one circumferential step. When rotating, the WSC performs two functions: the function of the main cutting motion and the function of the form-generating motion, in which the initial straight line of the cutter rack rolls without sliding along the initial circle of the shaft being machined [36-38]. In this form-generating motion, the product profile is formed. In addition, to process the shaft along its entire length, the feed movement along its axis is performed, equal to 0.5...1 mm per one revolution of the product.

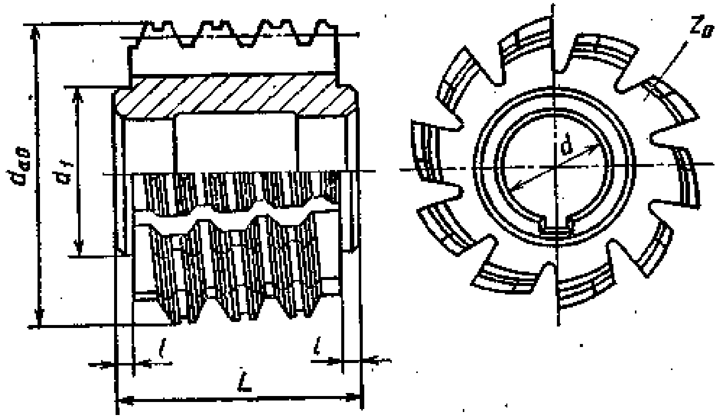


Fig. 2.2. Worm spline cutter

The input of initial data. The nominal dimensions of the splined shaft are presented in a unified form, for example:

$$d\text{ -}z \times d \times D \times b,$$

where the first position indicates the inner diameter along which the centering is carried out, then the value of the number of teeth *z*, inner diameter *d*, outer diameter *D* and tooth width *b* is given. For each splined shaft, tolerance fields are indicated, regulated by GOST 1139-80 (Table P 1.1).

Based on this initial information, the initial data is supplemented (according to GOST 1139-80 and ST SEV145-75) with such information (Fig. 2.2):

- *f* – chamfer along the outer diameter of the spline; in GOST the symbol *c* is used;

- *es*, *ei*, Δ – basic deviations and tolerance (ST SEV 145-75) for the nominal dimensions of the splined shaft;

- *a* – the length of the centering section along the inner diameter;

- d_1 – diameter of the beads (Fig. 2.2).

2.1. Calculation of the worm spline cutter elements

2.1.1. General information

The design of form-generating tools for processing straight-sided spline shaft profile teeth is carried out in the following sequence:

1) determination of the possibility of processing a given surface of the part (determination of the shape and positions of the machining centroid) and the choice of the method of profiling the cutter tooth [2, 18];

2) determination of the profile of the tool cutting edges;

3) determination of the structural dimensions and geometric parameters of the tool;

4) verification of the fulfilment of the set requirements when processing a part with a designed tool;

5) development of a working drawing of the tool and technical requirements.

When machining parallel spline shafts, their profile is formed as a result of generating around the spline by the cutting edges of the tool when rolling without sliding the centroid (initial straight line) of the workpiece (Fig. 2.3) [39, 40]. During the generation motion of the centroid, the provisions of the theory of conjugate profiles must be fulfilled:

- at the point of contact, the conjugate profiles must have a common tangent and normal;

- to the point of tangency must pass through the pole (P) of the engagement (profiling);

- lines drawn through all points of the workpiece profile, parallel to the centroid (initial straight line) of the tool, must intersect the profiling line, which is a set of points of contact of the tool cutting edge with the workpiece surface being machined.

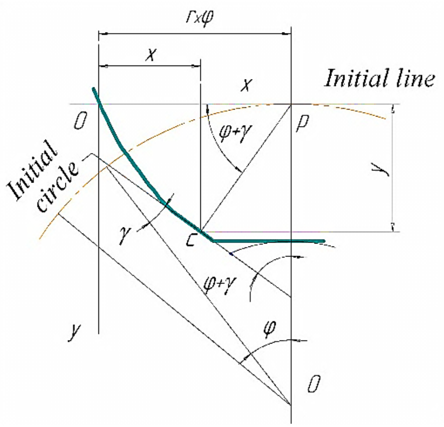


Fig. 2.3. Tooth profiling of a cutter

2.1.2. Determination of the design parameters of the splined shaft

Below are the ratios for determining the calculated dimensions:

1) calculated outer diameter of the splined shaft:

$$D_P = D_{\max} = D + es;$$

for chamfered shafts: $D_P = D_{\max} - 2f$,

where es – upper deviation from the nominal size;

f – spline chamfer;

$D_{\max}$ – the maximum permissible value of the outer diameter;

2) calculated inner diameter:

$$d_P = d_{\min} + 0.25\Delta d = d + ei + 0.25\Delta d,$$

where ei – lower deviation from the nominal size;

Δd – tolerance for the size of the inner diameter;

$d_{\min}$ – minimum permissible value of the inner diameter;

3) estimated thickness (width) of the tooth b_P:

$$b_P = b_{\min} + 0.25\Delta b = b + ei + 0.25\Delta b,$$

where Δb – tolerance for the tooth width size *b*.

The straight profile of the spline is determined by the profile angle γ (Fig. 2.4) between the straight profile and the radius drawn to the point under consideration. For different points of the same profile, the angles are different and decrease as the point under consideration moves away from the centre of the part along with the profile [41, 42].

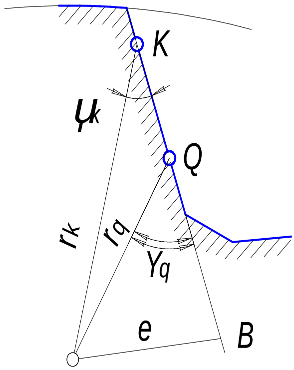


Fig. 2.4. Spline shaft profile angle

For a shaft with parallel splines, the profile angle γ is

$$\sin\gamma = \frac{b_P}{D_W},$$

where D_W – minimum diameter of the pinion pitch circle of a rectilinear profile, determined in this way:

$$D_W = \sqrt{D_P^2 - 0.75 b_P^{\ 2}}.$$

2.1.3. Analytical determination of the cutter tooth profile

The analytical method for determining the profile of the Parallel Spline Shaft Hob (PSSH) is based on the calculation of the coordinates of the profile points C_i (Fig. 2.3) [43-45]. The equation for calculating coordinates $C_i(x_i, y_i)$ is:

$$X = R_W\left\{\varphi - \left[\sin(\varphi+\gamma) - \sin\gamma\right] \times \cos(\varphi+\gamma)\right\};$$

$$Y = R_W\left[\sin(\varphi+\gamma) - \sin\gamma\right] \times \sin(\varphi+\gamma),$$

where $R_W = \dfrac{D_W}{2}$ – the radius of the pitch circle;

φ – the angle of rotation of the spline shaft (Fig. 2.5) until it touches the cutter profile at a point *C*.

The theoretical profile of the WSC cutting edge to simplify manufacturing (dressing abrasive disk when grinding the profile) is most often determined by an arc of one circle or tangent arcs of two or less often several circles, replacing the theoretical profile curve. For such a replacement, three points A_0, A_1 and A_2 are selected on the theoretical profile (Fig. 2.3) and through which the circle is drawn – determine its radius r_0 and coordinates of the centre X_0 and Y_0.

The origin of coordinates is taken as one point $A_0(0,0)$, the second $A_1(x_1, y_1)$ is chosen approximately in the middle of the profile and the third $A_2(x_2, y_2)$ is close to the apex of the tooth profile.

$$y_1 = 0.45h; \quad y_2 = 0.9h,$$

where *h* – the profile height is determined by the dependence:

$$h = \frac{D_W - d_P}{2}.$$

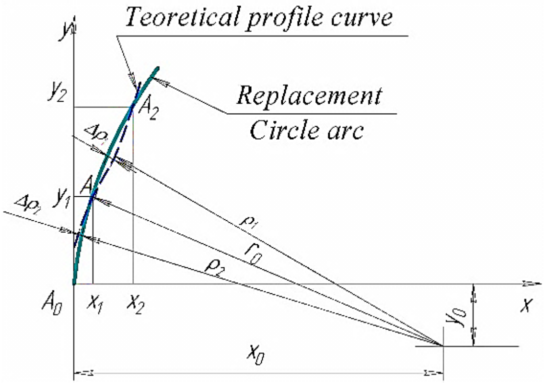


Fig. 2.5. Replacing the theoretical WSC-tooth profile

Substituting y_1 and y_2 into the equation for determining the y coordinates (2.1 and 2.2), the rotation angles of the spline shaft φ_1 and φ_2 before touching the cutter profile at points A_1 and A_2, similarly to point C shown in Fig. 2.1

$$\sin(\varphi_1 + \gamma) = \frac{\sin\gamma}{2} + \sqrt{\frac{\sin^2\gamma}{4} + \frac{y_1}{R_W}}\ ; \qquad (2.1)$$

$$\sin(\varphi_2 + \gamma) = \frac{\sin\gamma}{2} + \sqrt{\frac{\sin^2\gamma}{4} + \frac{y_2}{R_W}}. \qquad (2.2)$$

The abscissas of the points A_1 and A_2, define:

$$x_1 = R_W\left\{\varphi_1 - \left[\sin(\varphi_1 + \gamma) - \sin\gamma\right] \times \cos(\varphi_1 + \gamma)\right\};$$

$$x_2 = R_W \left\{\varphi_2 - \left[\sin\left(\varphi_2 + \gamma\right) - \sin\gamma\right] \times \cos\left(\varphi_2 + \gamma\right)\right\}.$$

The ordinate of the circle centre passing through the points A_0, A_1 and A_2 (calculation accuracy up to 0.000001 mm)

$$Y_0 = -\frac{(x_2^2 + y_2^2)x_1 - (x_1^2 + y_1^2)x_2}{2(x_2 \times y_1 - x_1 \times y_2)}.$$

The abscissa of the circle centre passing through the points A_0, A_1 and A_2:

$$X_0 = \frac{(x_2^2 + y_2^2)y_1 - (x_1^2 + y_1^2)y_2}{2(x_2 \times y_1 - x_1 \times y_2)}.$$

The radius of the replacement circle r_0:

$$r_0 = \sqrt{X_0^2 + Y_0^2}.$$

2.1.4. Determining the accuracy of replacing a theoretical profile with a circular arc

The magnitude of the error at two points with the maximum deviation of the arc from the theoretical profile is calculated (Fig. 2.3). The position of these points is coordinated by the angles of rotation of the spline shaft φ_{m1} and φ_{m2}:

$$\varphi_{m1} + \gamma = A + \sqrt{A^2 + B};$$

$$\varphi_{m2} + \gamma = A - \sqrt{A^2 + B},$$

where $A = \dfrac{R_W \cdot \gamma + x_0}{2\left(R_W + \dfrac{y_0}{3}\right)}$; $B = \dfrac{y_0}{R_W + \dfrac{y_0}{3}}$.

When calculating the parameters A and B – y_0 with their sign (usually a minus) are substituted.

The abscissas and ordinates of the points with the greatest deviation using the following dependencies are calculated:

$$X_{m1} = R_W \left\{\varphi_{m1} - \left[\sin(\varphi_{m1} + \gamma) - \sin\gamma\right] \times \cos(\varphi_{m1} + \gamma)\right\};$$

$$X_{m2} = R_W \left\{\varphi_{m2} - \left[\sin(\varphi_{m2} + \gamma) - \sin\gamma\right] \times \cos(\varphi_{m2} + \gamma)\right\};$$

$$Y_{m1} = R_W \left[\sin(\varphi_{m1} + \gamma) - \sin\gamma\right] \times \sin(\varphi_{m1} + \gamma);$$

$$Y_{m2} = R_W \left[\sin(\varphi_{m2} + \gamma) - \sin\gamma\right] \times \sin(\varphi_{m2} + \gamma).$$

The distance between the centre of the replacement circle and the points of the cutter profile, in which the deviation of the theoretical profile is $\Delta\rho_1$, $\Delta\rho_2$ and the radius of the replacement circle r_0 represents the replacement error:

$$\Delta\rho_1 = \sqrt{(x_{m1} - x_0)^2 + (y_{m1} - y_0)^2} - r_0;$$

$$\Delta\rho_2 = \sqrt{(x_{m2} - x_0)^2 + (y_{m2} - y_0)^2} - r_0.$$

Replacing a theoretical profile with an arc of a circle is permissible if:

$$\left|\Delta\rho_1\right| + \left|\Delta\rho_2\right| \le \frac{2}{3}\Delta b.$$

If this condition is not met, the theoretical profile with arcs of two circles is replaced (Fig. 2.4) [1]. The need for such a replacement usually arises when $h > 0.12R_W$. The coordinates of the points A_i of the replacement profile (arcs of two touching circles) are determined by the calculated dependencies [46], given in Appendix 2.

2.1.5. Calculation of the dimensions of the worm spline cutter profile in the normal section

The calculation of the dimensions is illustrated in Fig. 2.6.

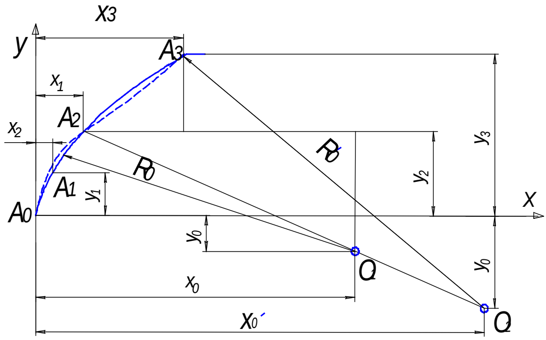


Fig. 2.6. Replacing a theoretical profile with arcs of two circles

1. Step of threads along the normal P_{nO}

$$P_{nO} = \pi Dw/z.$$

2. Thickness of the cutter tooth along the initial straight line *Sno* (S_2)

$$S_{nO} = D_W\left(\frac{\pi}{z} - \gamma_W\right).$$

3. Maximum cutter profile height $h_{\max}$:

$$h_{\max} = \frac{D_p - d_p}{2}.$$

4. Dimensions of the groove for the exit of the grinding disk v:

$$v = P_{nO} - (S_{nO} + 2f); \; u = 1.5\ldots3.0 \text{ mm}.$$

5. Chamfer angle at the root of the cutter tooth profile (flank) $\varepsilon_{ch} = 35^0$ for four to eight spline shafts. With an increase in the number of splines, the chamfer angle increases to $\varepsilon_{ch} = 45^0$.

6. Thickness of the cutter tooth S_x at any height h_x from the initial straight:

$$S_x = S_{no} - 2(x_o - r_o \cos\beta_x),$$

where $\sin\beta_x = \frac{|y_0| + h_x}{r_0}$.

In the drawing, S_x is usually set at a height of y_1 or y_2 (Fig. 2.6).

7. Height of the cutter tooth head to the tongue $h_{a'}$ (Fig. 2.7):

$$h_{a'} = \frac{D_w - d_p}{2}$$

8. Height of the cutter tooth head h_a (including antennae):

$$h_a = \frac{D_w \sin\alpha_f (\sin\alpha_f - \sin\gamma_{w)}}{2},$$

where α_f – max the value of the angular parameter at the root of the cutter tooth:

$$\alpha_f = \arccos\frac{\sqrt{d^2 - b_p{}^2}}{Dw}.$$

9. Chamfer height chamfer h_{ch}:

$$h_{ch} = 2f \cdot tg\varepsilon_{ch}.$$

10. Total height of the cutter tooth h_0:

$$h_0 = h_a + h_{ch} + u.$$

11. The height of the tongue h_t:

$$h_t = h_a - h'_a.$$

12. Tongue width b_t:

$$b_t = (0.8....1.0)h_t.$$

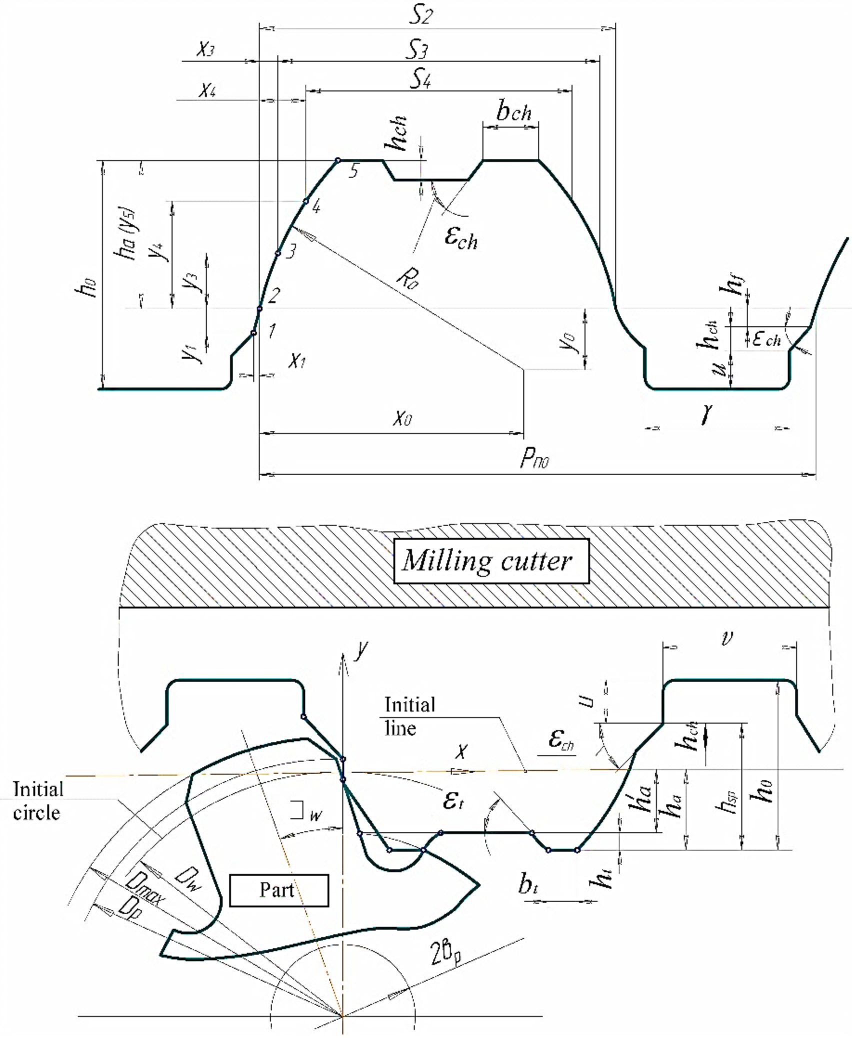


Fig. 2.7. Cutter profile in the normal section

2.1.6. Geometric and structural elements of a worm spline cutter

The main provisions on the choice of overall and design dimensions of wormwheel hob are also valid for the WSC cutters under consideration [47-49].

The WSC design parameters are selected following GOST 8027-86 based on the nominal dimensions of the spline connection $\{z \times d \times D\}$ and taking into account the type of connection. The following parameters of the cutter are set (Fig. 1.2):

d_{ao} – addendum diameter;

L – cutter length;

D – diameter of the mounting bore;

d_1 – diameter of the bead;

ℓ – length of the bead;

z – number of cutter teeth (number of chip grooves).

When choosing the diameter of the mounting bore, which serves for fastening and basing the cutter on the mandrel by the normal range are guided to GOST 9472-90.

In design practice, the relations are also used:

$$d = (0.2...0.45)d_{ao}.$$

The WSC geometry is also selected taking into account the recommendations of GOST 8027-86.

1. The front rake angle γ_{ao} of the finishing cutter is taken equal to 0 due to the high precision of spline shaft profiling; for a roughing cutter, it can be selected depending on the material to be cut within the range $\gamma_{ao} \leq 10^0$.

2. Back clearance angle at the teeth tip: $\alpha_{ao} = 9^0....11^0$.

3 The back clearance angle on the lateral sides of the profile α_l with sufficient for practical purposes accuracy is determined from the expression:

$$tg\alpha_l = tg\alpha_{ao}\sin\varphi_w; \;\; \text{tg}\varphi_w = \frac{|y_o|}{x_o}.$$

The smallest value of the lateral back clearance angle is at points on the root of the cutter tooth, processing the top of the shaft profile. The back clearance angle must be $\alpha_{ao} \geq 1^0 30'$.

4. The amount of relief K (rounded up to 0.5mm):

$$K = \frac{\pi d_{ao}}{z} \cdot tg\alpha_{ao}.$$

Since worm spline cutters are made with a grinding profile of the teeth, they make a double relief to avoid getting a saddle on the teeth.

5. The amount of additional relief K_1: K_1 = (1.2 ... 1.5) K.

6. Depth of a chip groove H_g

$$H_g = h_0 + \frac{K_1 + K_2}{2} + r_g,$$

where r_g – radius of the chip groove, taken $r_g = 1.2...1.5$ mm.

7. The angle of the chip groove δ is taken in the range 22^0 ... 25^0.

8. The grinding part of the WSC tooth C_o (Fig. 2.8), providing the required profile accuracy, must be at least 1/3 of the tooth length in the outer diameter:

$$C_0 = \frac{1}{3} t_0,$$

where t_0 is the circumferential step is determined from the expression:

$$t_o = \frac{\pi d_{ao}}{z}.$$

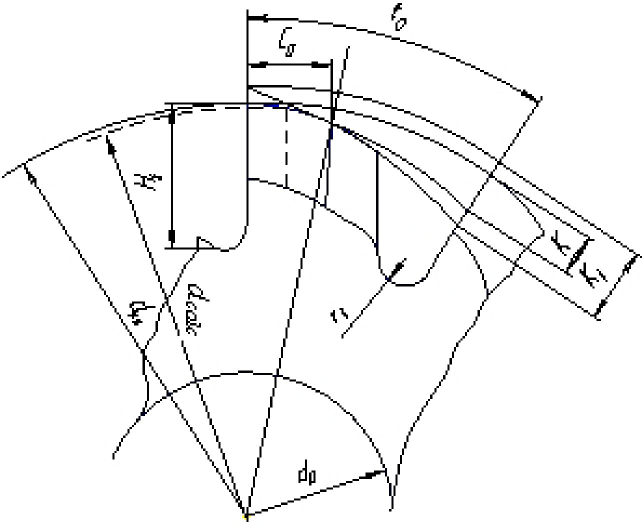


Fig. 2.8. Relieving the cutter

9. The length of the cutter L can be determined approximately:

$$L = (2\dots3)\, t_0 + (6\dots7) \text{ mm.}$$

This expression takes into account the part of the length required to reposition the cutter to increase its performance [50-52]. In addition, the length of incomplete turns on the sides of the cutter is taken into account.

10. The length of the grinding areas of the mounting bore:

$$\ell = (0.2...0.3)\, L,$$

with a smaller value for large L and smaller d_{ao}.

Undercut diameter d_2 (between ground areas)

$$d_2 = d + (1...2) \text{ mm.}$$

11. Estimated average diameter d_{calc}. as well as for WH cutters, it is taken in a section lagging behind the front surface of the groove by 1/8 of the circumferential step. Sometimes the calculated diameter is taken not in the middle of the cutter profile height, but tangentially to the pitch circle of the part (with an accuracy of 0.1 mm.):

$$d_{calc} = d_{ao} - 2h_a - (0.2....0.3)K.$$

12. The lead angle of the turn τ on d_{calc}:

$$\sin\tau = \frac{P_{no}}{\pi d_{calc}}.$$

13. Angle of inclination of helical chip grooves $\omega = \tau$ or $\omega = 0$. The direction of the helical grooves is opposite to the direction of the turn. Due to the large pitch of the spline shaft profiles, the cutter leads the angle of the turns τ to be greater than that of similar WH cutters for gear wheels. The turns lead angle can vary in the range $9^0...6^0$, and sometimes up to 10^0.

14. Pitch of helical chip grooves S_g (accuracy up to 1mm):

$$S_g = \pi d_{calc} ctg\omega.$$

15. Pitch of turns along the P_{xo} axis (accuracy up to 0.001mm):

$$P_{xo} = \frac{P_{no}}{\cos\tau}.$$

16. The diameters of the addendum and dedendum circles are determined in the same way as for the WH cutter:

$$d_{ao} \geq 2H_g + 2p + d;$$

$$d_{fo} \geq d_{ao} - 2H_g,$$

where *p* – thickness of the cutter body, which must be sufficient to ensure the strength of the cutter, it is taken at least 0.25...0.30 of the mounting bore diameter *d*.

2.2. Design of a worm spline cutter for straight-sided spline shafts of accuracy class “A”

The main dimensions of spline joints are regulated by GOST 1139-80, which provides for three series of joints – light, medium and heavy; with centering of the shaft and sleeve – along with the outer diameter *D* (1st method), inner diameter *d* (2nd method) and along the sides of the teeth *b* (3rd method).

Based on the data obtained as a result of calculations, according to the considered methodology, the design of worm spline cutters using the "KOMPAS" system is carried out.

Start of design

1. Create an exercise directory in your folder.
2. Start the *CAD-MILLING CUTTER library*.
3. From the main menu, select *Project* / *Wormwheel hob for ...* / *Spline shafts*
4. When prompted by the system, select the created directory and enter the name of the result file. (For this example, file_002).
5. Click the *Save* button.

Setting initial data

In the window "*Main parameters of the shaft and cutter*" (Fig. 2.9), set the following parameters:

1. Milling cutter for the spline shaft (the joint series is indicated) – *light series*.
2. Accuracy class *d* – *A*.
3. The nominal size of the series – *8×36×40*.

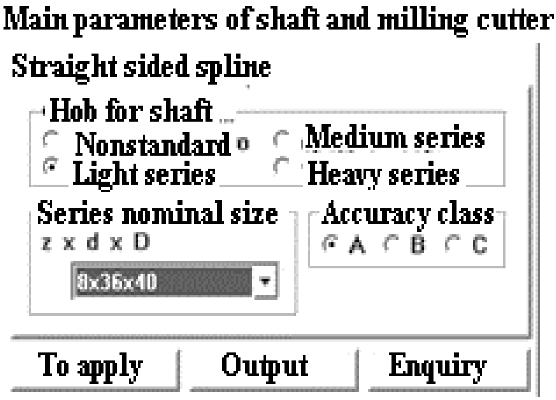


Fig. 2.9. The main parameters of the shaft and cutter

Click the *Apply* button.

In the "*Spline shaft parameters*" window (Fig.2.10) set the following parameters [53, 54]:
1. Centering method – 1.
2. Tooth thickness, *b* – 7 mm, tolerance field: 0.13; 0.035.
3. Outside diameter, *D* – 40 mm, tolerance field: 0.31; -0.47.
4. Inner diameter, *d* – 36 mm, tolerance field: -0.05; -0.089.
5. Chamfer, *c* – 0.4 mm, tolerance range: 0.2; 0.
6. The minimum root groove length, *a* – 3.46 mm.

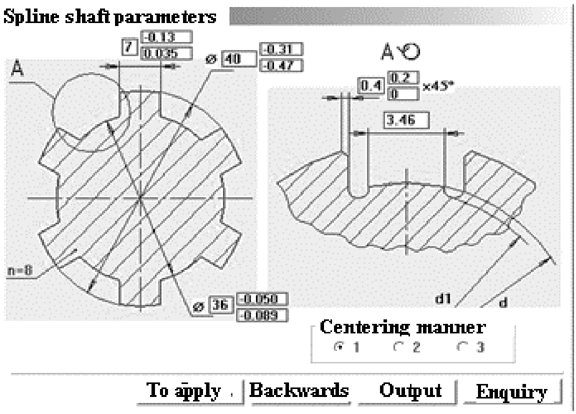


Fig. 2.10. Spline shaft parameters

Click the *Apply* button.

In the "*Straight section of the profile*" window (Fig.2.11) set the following parameters:

1. We accept: D_{pc} – the diameter of the pitch circle.
2. Profile step (p. 3.4), t_n (P_{nO}) – 38.7726949 mm.

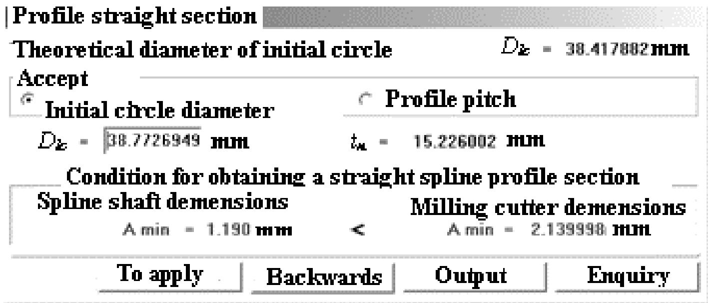


Fig. 2.11. Straight section of the profile

Click the *Apply* button.

Profile calculation

In the "*First check method*" window (Fig.2.12), the main parameters of the profile are displayed.

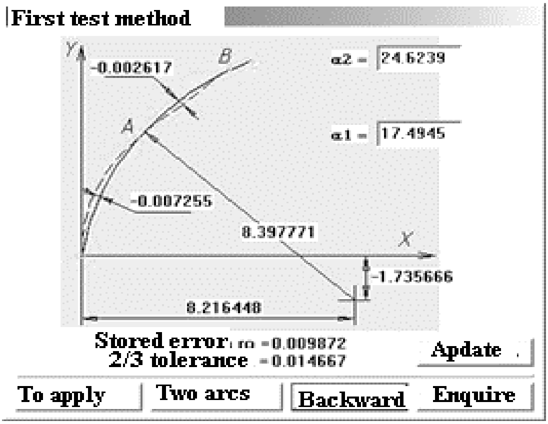
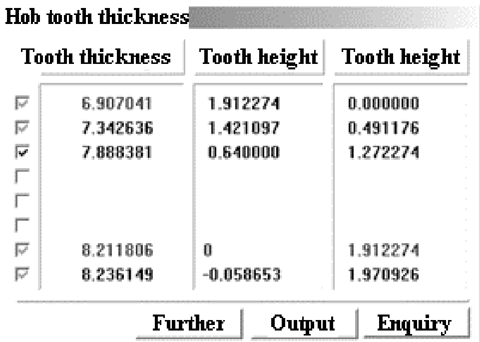


Fig. 2.12. First check method

Click the *Apply* button. The system will check the second method and present the results.

In the window "*Cutter tooth thickness*" (Fig.2.13), click on a free square, and the system will ask for the height parameter.



Hob tooth thickness

	Tooth thickness	Tooth height	Tooth height
☑	6.907041	1.912274	0.000000
☑	7.342636	1.421097	0.491176
☑	7.888381	0.640000	1.272274
☐			
☐			
☐			
☑	8.211806	0	1.912274
☑	8.236149	-0.058653	1.970926

Further | Output | Enquiry

Fig. 2.13. Cutter tooth thickness

In the window "*Height of additional profile size*" (Fig.2.14) specifies the value of the height h_x from the basic line – 2 *mm*. Click the *Apply* button.

After obtaining the tooth thickness reading, click *Next*.

In the "*Profile of teeth in normal section*" window, analyze the received data, if they correspond to the specified ones, click the *Apply* button.

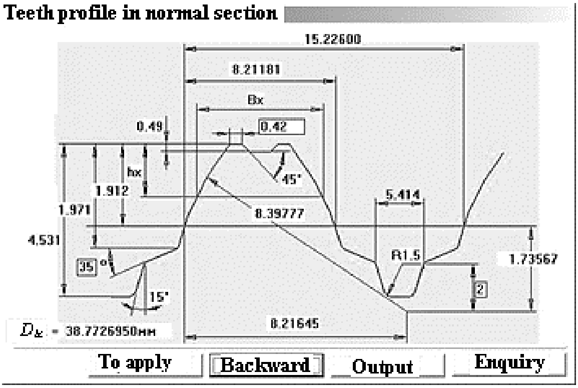


Fig. 2.14. Tooth profile in the normal section

In the "*Tooth angles*" window (Fig.2.15) click the *Apply* button.

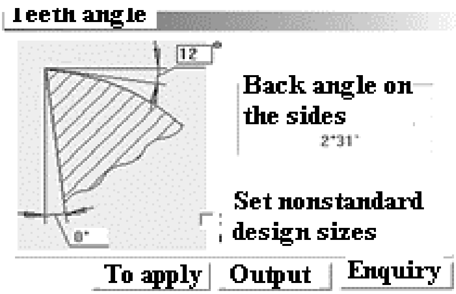


Fig. 2.15. Tooth angles

In the "*Tooth geometry*" window (Fig.2.16) set the following parameters (p. 2.6):

1. The size of the relief – *6.5 mm*.
2. The amount of additional relief – *8 mm*.
3. The depth of the groove – *13.138 mm*.

Click the *Apply* button.

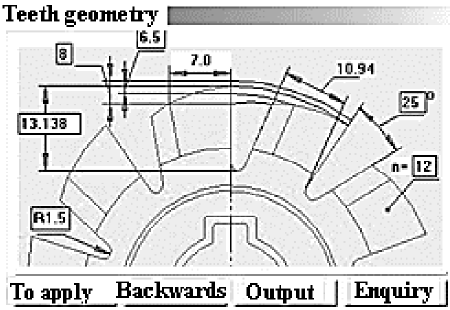


Fig. 2.16. Tooth geometry

In the "*Keyway*" window (Fig.2.17, click the *Apply* button.

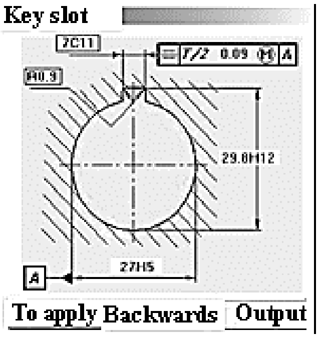


Fig. 2.17. Keyway

In the "*Construction dimensions*" window (Fig.2.18), change the length of the mounting bore segment by *20* mm.

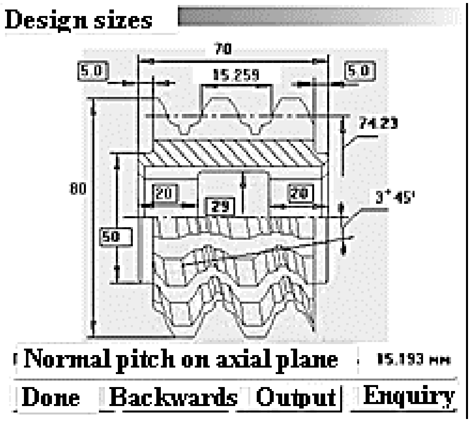


Fig. 2.18. Design dimensions

Click the *Finish* button.

When prompted for the cutter number, enter *002*.

Click the *Apply* button.

Fig. 2.19 and Fig. 2.20 shows a drawing of a worm spline cutter.

Obtaining documentation

From the main library menu, select *Documentation/Create Documentation.*

At the request of the system, select the created directory and select the results file: *file_002.rzl*.

Click the *Open* button. Wait, after creating the documentation, the system will display the message "*Documentation has been created*".

After creating the documentation, the directory will contain a text file *shb2.txt* (opened with any text editor) and graphic files: *fsh.cdw* and *fsh1.cdw*; check out the generated documentation.

For example, select *Documentation/Text Editor* from the main menu of CAD MILLING CUTTER (CMC) and open the file *shb2.txt*. From the main menu of CMC select *Project/Exit* and view the created drawings in the "KOMPAS-GRAPHIK" environment (*files fsh.cdw* and *fsh1.cdw*).

The calculation results of the worm spline cutter are presented in Appendix A2.

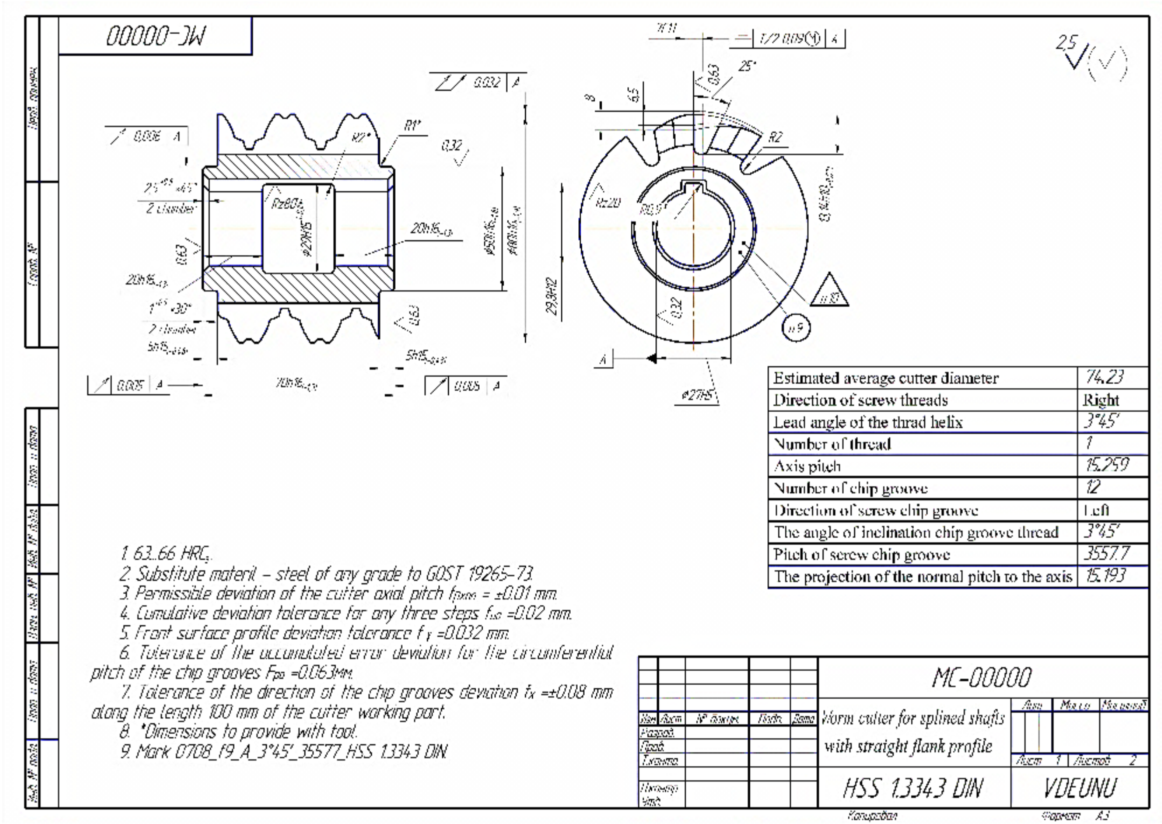


Fig. 2.19. Drawing of a worm spline cutter

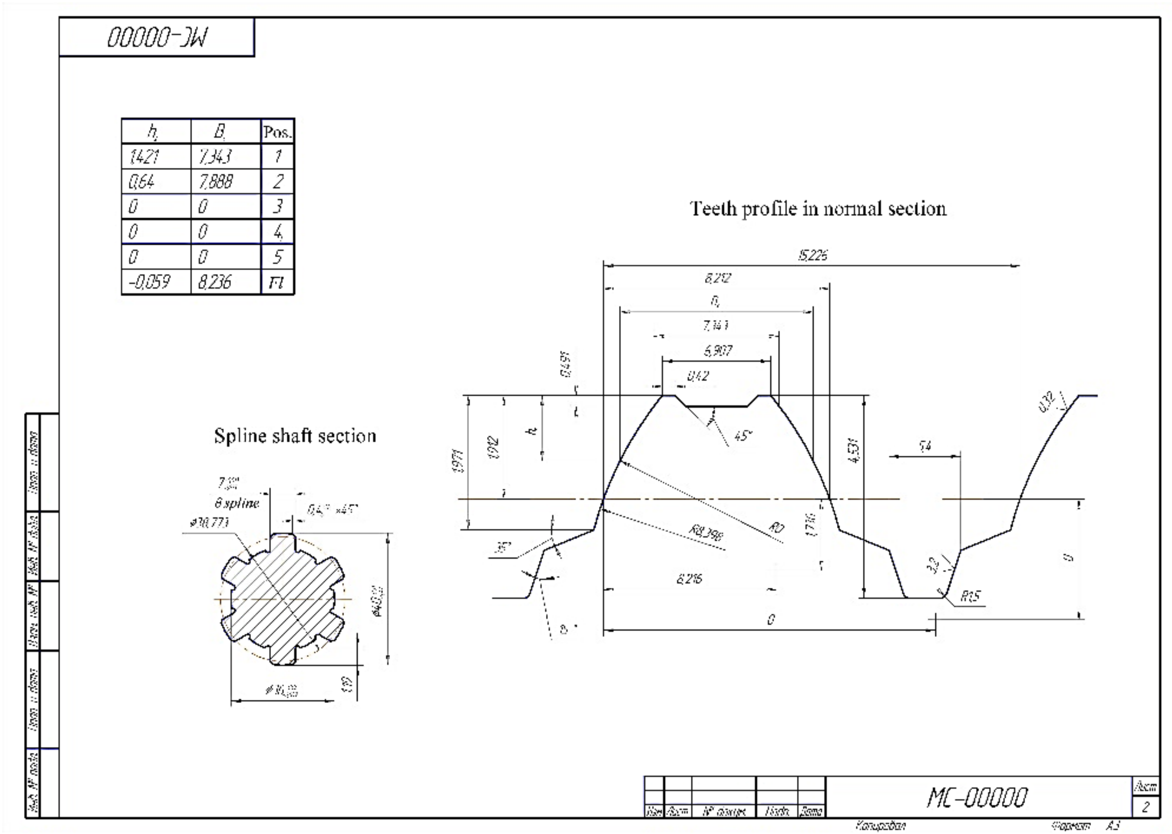


Fig. 2.20. Worm spline cutter: tooth profile

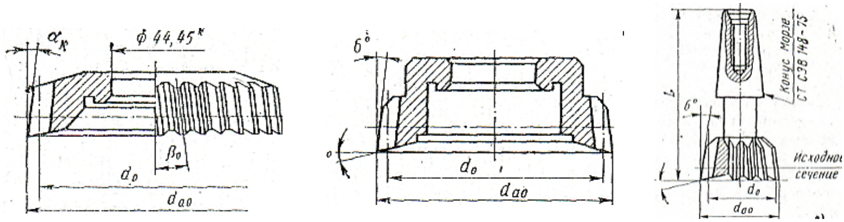
3. DESIGN OF DISK-TYPE GEAR SHAPER CUTTER USING THE KOMPAS-3D SYSTEM

3.1. General Provisions

A shaper is a cutting tool based on a correction (correlation adjustment) gear wheel with appropriate sharpening angles (Fig. 3.1).

The area of use of shapers is cutting various cylindrical gears of 6 ... 8 degrees of accuracy, gear sectors and racks, spline joints and machining of parts with an arbitrary profile. The most widespread shapers are for cutting involute teeth of wheels [55-57].

The use of the gear shaping process is especially effective for processing internal gear, chevron and block wheels (Fig. 3.1, b).



a b c

Fig. 3.1. Types of shaper gear cutters: a – disk-type;
b - deep counter-type; c - shrank-type

Compared to gear milling cutting, all other things being equal, gear shaping provides higher accuracy and law roughness of the machined surface, but lower cutting performance.

Gear shaping is carried out according to the centroid bending method by reproducing the kinematic process of the actual, tool engagement (shaper producing wheels) with the gear being machined, in which their centroids (pitch circles) roll one over the other without sliding.

Depending on the nature of the workpieces being processed, the cutters are divided into three groups:

1. Spur shaper – for cutting spur gears.
2. Helical shaper – for cutting helical gear and chevron wheels.
3. Special – for cutting toothed parts with an arbitrary profile.

By design, following GOST 9323-79, there are 5 types of cutters:

1 – spur disc-type shaper cutters of accuracy classes AA, A and B for the 6th, 7th and 8th degrees of wheel accuracy;

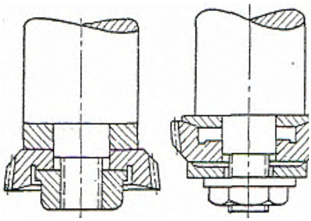
2 - disk helical shaper cutters – accuracy classes A and B for the 7th and 8th degrees of wheel accuracy (Fig. 3.1, a);

3 – deep-counter shaper cutter with spur teeth – accuracy classes AA, A and B for the 6th, 7th and 8th degrees of wheel accuracy (Fig. 3.1, b);

4 – shank shaper with spur teeth – accuracy classes A and B for the 7th and 8th degrees of wheel accuracy;

5 – shank shaper with helical teeth shank shaper – accuracy class B for the 8th degree of wheel accuracy (Fig. 3.1, c).

The shaper is mounted in the ram (cutter spindle) of the gear shaping machine (Fig. 3.2) and performs a reciprocating (back-and-forth) main cutting motion V_p [58-60].

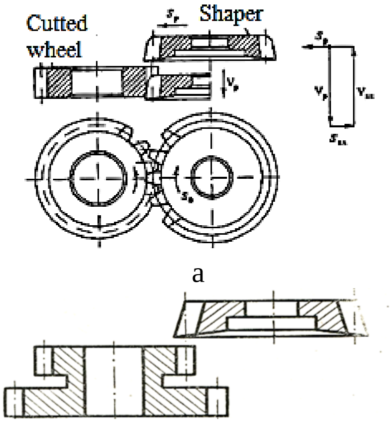


a b

Fig. 3.2. Ways to mount the shaper: a – thread bush; b – bolt fixture

The form-generating process (Fig. 3.3) by the synchronous rotation of the shaper and the workpiece with circular feeds S_0 and S_1 due to the kinematics of the machine in such a way; that when the shaper is rotated by one tooth, the workpiece is also rotated by one tooth is provided.

The shaper undercut into the machining depth is cyclically ensured by the radial feed S_p carried out at the end of the idle stroke, in which the shaper is retracted from the workpiece by a distance S_{xx} to avoid friction of the tooth rear surface and the machined surface [61-63].



a

b

Fig. 3.3. Scheme of gear shaping of spur gears:
a – cutting of a gear wheel; b – cutting a gear block

3.2. Design of spur disc-type shaper cutters

In various literary sources for the design of shaper cutters, various designations of their main elements are used. Table 3.1, along with GOST, the most used designations are presented (in brackets). To ensure the possibility of cutting, the shaper is given a slightly modified appearance compared to a conventional gear wheel – they create cutting edges and slightly increase the height of the tooth head. The shaper receives cutting surfaces due to the formation of cutting angles: front rake γ, back clearance α_{tp} and lateral back clearance α_l (Fig. 3.4) .

Table 3.1

The main elements of the cutter and wheels

Name of elements	Designation of elements		
	Shaper cutter	Wheel	Wheel paired
Module, mm	$m_0\,(m)$	m	m
Teeth number	$z_0\,(z_t)$	z_1	z_2
Engagement angle, deg	α_w	α	α
Pressure angle on the tooth head, deg	$\alpha_{a0}\,(\alpha_{et})$	α_{a1}	α_{a2}
Coefficient of displacement of the basic contour	$X_0\,(\xi_t)$	ξ_1	ξ_2
Base circle diameter, mm	d_{b0}	d_{b1}	d_{b2}
Addendum circle diameter, mm	$d_{a0}\,(d_{e0})$	d_{a1}	d_{a2}
Dedendum circle diameter, mm	$d_{f0}\,(d_{i0})$	d_{f1}	d_{f2}
Pitch circle diameter, mm	$d_0\,(d_r)$	d_1	d_2
Tooth thickness along the arc of the pitch circle, mm	$S_0\,(S_r)$	S_{r1}	S_{r2}
Shaper cutter profile angle, deg	$\alpha_0\,(\alpha_t)$		
Tooth head height coefficient	$h_a'\,(h_t')$	h_{a1}^*	h_{a2}^*
Tooth root height coefficient	$h_f'\,(h_t'')$	h_{f1}^*	h_{f2}^*
Distance of the basic section from the front surface, mm	A		

The profile of the shaper teeth in any section must be outlined along the involute formed from the same basic circle – d_{b0}. This is achieved when the lateral surfaces of the teeth represent helical involute surfaces due to a corresponding change in the thickness of the tooth [64-67]. At the same time, when re-sharpening the shaper along the front surface of the teeth. due to the presence of back angles, there is a constant change in some shaper parameters: a decrease in the addendum diameter d_{a0} and the thickness of the teeth on the pitch circle (S_0; in several sources S_r) and on the tooth apex (S_{a0}), etc. For this reason, when calculating the shaper, section I - I, called the basic (original), spaced from the front end II-II of an uncut new shaper at a distance *A* (Fig. 3.4). In section, I-I, the shaper represents an uncorrected gear wheel, with elements exactly corresponding to the tooth elements of the wheel being machined. The greater the distance A, which is called the basic one, the greater the margin for re-sharpening the shaper, but with an increase in A, the correct formation of the active part of the involute profile of the wheel cut teeth and sharpening of the shaper teeth at the tip may occur. Determination of the optimal value of the basic distance *A* is the main task in the process of calculating the shaper.

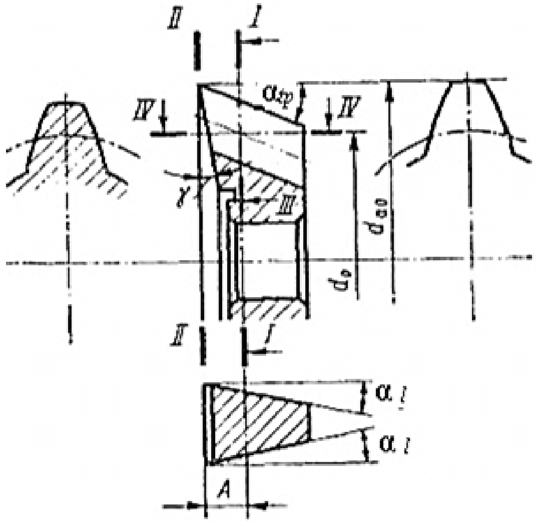


Fig. 3.4. Geometrical parameters of a disc spur shaper cutter

The calculation of the spur shaper cutter is carried out in the following sequence:

1. The nominal (preliminary) pitch diameter d_{0n} is taken according to the passport data of the gear shaping machine (Table 3.2) and following

GOST 9323-79. Depending on the size of the modulus *m*, the following pitch diameters for the disc shaper-type cutter are recommended (Table 3.2).

Table 3.2

Diameter sizes of shaper-type cutter

Machine tool	Largest wheel parameters		Centre distance shaper-wheel	Shaper mounting bore diameter	Shaper pitch diameter
	m	Outer diameter			
5A12	4	208	-	31.75	80
514; 5M14	6	500	0…350	44.45	80
5140	8	500	0…355	44.45	100

Table 3.3

Standard nominal pitch diameters d_{0n}

Nominal pitch diameter d_{0n}, mm	80	100	125	160	200
Module *m*, mm	1…5.0	1…6.5	5…9	8…10	10…12

1. The number of shaper teeth: $z_0 = d_{0n} / m_0$; the obtained z_0 values are recommended to be rounded to the nearest whole. In GOST 9323-79 the recommended values of z_0 are given.

The optimal number of teeth of the shaper is z_0 = 15 ... 40. This number of teeth allows cutting gears in almost the entire range of sizes. However, when cutting internal gear wheels, as well as external gear wheels of large modules, shapers with z_0 <15 are used. On the other hand, to increase the durability of the shapers, it is desirable to increase the number of its teeth to 75 ... 80. In these cases, it is necessary to check the shapers for undercutting the roots of the teeth and the interference of the profiles with the transition curves of the conjugating wheels cut by such shapers [68, 69]. The interference of the profiles as any incorrect touch of them outside the active section of the engagement line or the intersection of the theoretical profiles of two conjugating wheels is understood.

3. Refined pitch circle diameter: $d_0 = z_0 \cdot m_0$.

The pitch circle diameter d_0 must be taken as small as possible, since the smaller this diameter, the smaller the overhang of the cutting edges relative to the ram axis, the more rigidly and stably the shaper will be fixed. At the same time, with a decrease in the pitch circle diameter, there is a risk of increasing distortion in the involute. It is necessary to choose such a pitch circle diameter that would ensure both stable operations of the shaper and sufficient accuracy of the involute cut wheel tooth profile. The actual pitch diameter d_0 should be as small as possible from the nominal, and the number of teeth should be chosen as even as possible (to simplify the manufacturing and control technology).

4. The diameter of the theoretical base circle: $d_{b0} = d_0 \cdot \cos\alpha_0$. The accuracy of calculating d_{b0}, taking into account the distortion from sharpening, is 0.000001.

5. The back clearance (relief) angle at tip α_{tp} and the front rake angle γ. For standard cutters, $\alpha_{tp} = 6^0$ is taken; $\gamma = 10^0$ when cutting teeth on steel wheels and $\gamma = 5^0$ on cast iron wheels. Research prof. V.M. Matyushin showed that with an increase in the relief angle α_{tp} up to 9^0, and the front rake angle γ up to $12...17^0$, the durability of roughing shapers increases by 2 times, and of gear-finishing shapers up to 1.3 times.

6. Profile angle of the shaper: $\alpha_0 = \alpha$, where α is the gearing angle of the wheel (the angle of the main profile of the basic contour of the gear wheels according to GOST 13755-81). This equality is valid at zero rake angle $\gamma = 0$. If there is a rake angle on the cutter that is not equal to zero, the profile of the shaper in the section perpendicular to its axis will not coincide with the profile of the front surface projection onto the end face of the wheel being cut, i.e. $\alpha_0 \neq \alpha$. To obtain a given profile angle α on a

wheel cut, the shaper with an actual profile angle α_0 determined by the formula must be made [1]:

$$\alpha_0 = arctg \frac{tg\alpha}{1 - tg\alpha_{tp} \cdot tg\gamma}.$$

The calculation with an accuracy of 0.000001, and the obtained value of α_0 is rounded up to 1" is carried out.

7. Lateral back clearance angle: $tg\alpha_l = tg\alpha_{tp} \cdot tg\alpha_0$. This angle in the section of the shaper tooth along the indexing cylinder is measured (Fig. 3.4). The intersection lines of the tooth lateral surfaces with the cylinder are helical lines with an angle of inclination α_l. In this case, the lateral surfaces are involute helical surfaces. To determine this angle, consider a scan of the resulting section on a plane (Fig. 3.5).

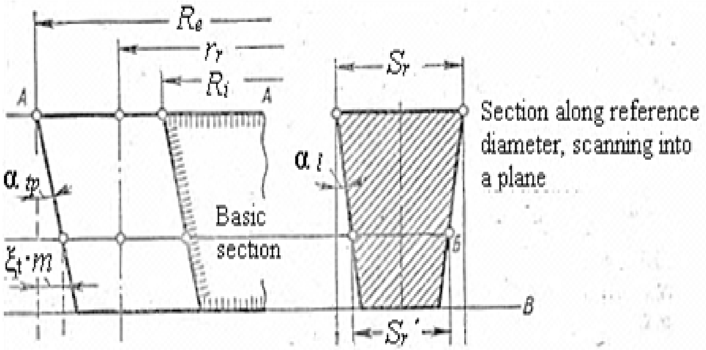


Fig. 3.5. Initial cross-section of the shaper

Then the helical lines will turn into straight lines, inclined to the vertical at an angle α_l, which for the standard geometry of the shaper ($\alpha_{tp} = 6^0$ and $\alpha_0 = 20^0$ 10'14.5") takes the value $\alpha_l = 2^0$12'40". The calculation of the angle α_l with an accuracy of 0.000001, and the obtained value of α_l is rounded to 1" is carried out.

8. Determination of the shaper parameters in the basic section I - I (Fig. 3.4).

In this section, the dimensions of the shaper teeth – the thickness of the tooth along the arc of the pitch circle S_r, the height of the head h_{a0} and the root h_{f0} will be equal to the corresponding dimensions of the basic contour of the gear being cut.

8.1. Shaper outer diameter:

$$d_{eI}\ (d_{a0I}) = d_0 + d_1 - d_{f1},$$

where d_r and d_f are the diameters of the pitch circle and the dedendum circle of the cut wheel, respectively.

8.2. The thickness of the teeth of the shaper (Fig. 3.6) on the pitch circle:

$$S_r\ (S_{0\mathrm{I}}) = 0{,}5 \cdot \pi m_0 + \Delta S_0,$$

where ΔS_0 – an increase in the thickness of the shaper's tooth to create the necessary lateral clearance in the engagement of the cut wheels (Table 3.4).

Table 3.4

Thickening of the teeth

Module m, mm	Thickening of teeth ΔS_0, mm	Module m, mm	Thickening of teeth ΔS_0, mm
1.25…2.5	0.127	6.5…10.0	0.214
2.75…4.0	0.161	11.0…16.0	0.247
4.25…6.0	0.175	18.0…20.0	0.349

8.3. The height of the tooth head is $h_{a0\mathrm{I}} = 1.25\ m$ – for small modules cutters ($m = 2.5$ inclusive) and $h_{a0\mathrm{I}} = 1.3m$ – for large modules cutters.

The height of the tooth root $h_{f0\mathrm{I}}$ should be the same as the height of the head. The height of the shaper's tooth in the basic section is $h_{0\mathrm{I}} = h_{a0\mathrm{I}} + h_{f0\mathrm{I}}$. Counting according to clauses 8.2 and 8.3 with an accuracy of 0.0001 is made.

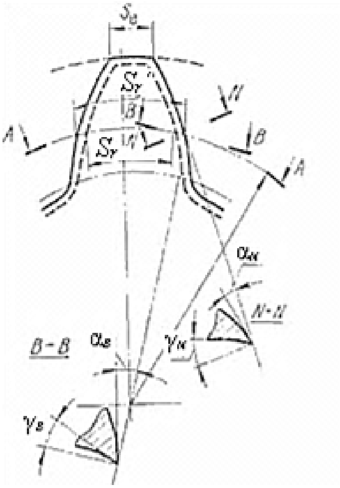


Fig. 3.6. Shaper tooth profile

9. Determination of the value of the basic distance A (Fig. 3.4).

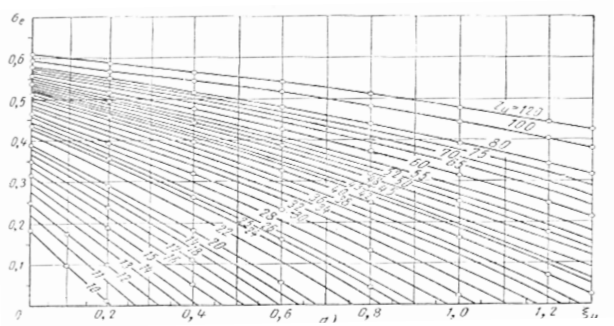
The selection criterion is to maximize the value of the basic distance *A*, which provides an increase in the service life of the tool and a decrease in the risk of undercutting the tips of the cut wheel teeth, especially when using cutters with a small number of teeth [70, 71]. At the same time, with an increase in the value of *A*, the transition curves at the root of the cut wheel teeth are increased, which can lead to a deterioration in the engagement of the cut wheel with the paired wheel (interference along the transition curves). With increasing distance *A*, the width of the tooth at the apex of the new shaper decreases, which is the main factor limiting the value of the basic distance.

To determine the value of *A*, three methods are used:

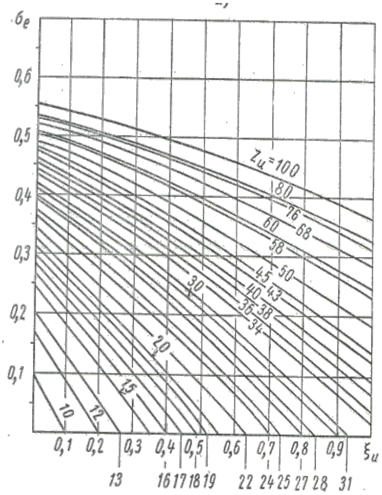
1) interpolation, when the radii of the addendum circles and the thickness of the tooth on them are determined for two arbitrary values of the distances A' and A'' from the plane of the front end. From the obtained values of S'_{a0} and S''_{a0} and the required value of S_{a0}, by interpolation, the value of *A* is found.

2) graphical, based on the available diagrams (Fig. 3.7), developed for certain design parameters of the shaper cutters.

3) analytical, depending on the thickness of the shaper's tooth in the basic section and the plane of the front end.



a



b

Fig. 3.7. Diagrams for determining the permissible shift of the original contour: a – $h_a^* + c^* = 1.25$; б – for $h_a^* = c^* = 1.3$

The permissible value of the thickness of the shaper teeth on the addendum circle S_e (Fig. 3.6) of the new shaper by the formula can be roughly determined [1]:

$$S_e = \sqrt{0{,}2594 \cdot m - 0{,}0375}\ .$$

Another way of determining S_e depending on the module m_0 is tabular (Table 3.5).

Table 3.5

Choosing the thickness of the shaper tooth S_e

m_0	S_e	m_0	S_e
0.1…0.9	(0.6…0.5) m	3.0…4.0	(0.30…0.25) m
1.0…1.5	(0.46…0.41) m	4.25…6.0	(0.25…0.20) m
1.75…2.75	(0.40…0.31) m	7.0…8.0	(0.20…0.10) m

In turn, the thickness S_e is represented in terms of modulus through the coefficient σ_e:

$$S_e = \sigma_e \cdot m;\ \sigma_e = S_e/m.$$

The permissible shift (displacement) of the basic contour of the new shaper ξ_t (X_0) is determined depending on the value of σ_e, the number of shaper teeth z_t and the coefficients of the tooth head height h_a^* (taking into account the coefficient of the radial clearance c') according to diagrams Fig. 3.7, a ($h_a^* + c^* = 1.25$) and Fig. 7, b ($h_a^* = c^* = 1.3$). There is also a simplified analytical option for determining the displacement:

$$\xi_e \approx 0.01 \cdot z_0 - 0.1.$$

From the criterion of maximizing the basic distance *A*, it follows that it is necessary to select the largest displacement, which increases the quality of the processed surface and the profile accuracy of the wheels being cut [72-74]. Distance *A* and displacement ξ_t, as seen in Fig. 3.4 and Fig. 3.5 are interconnected by dependencies:

$$A = \frac{\xi_t \cdot m_0}{tg\alpha_{tp}}.$$

The displacement magnitude of the basic section *A* is selected from the condition of ensuring the required thickness of the tooth on the addendum circle of the new shaper and obtaining the profile of the cut wheel teeth, ensuring its correct engagement with the paired wheel. Approximately the minimum thickness of the tooth (Fig. 3.6) on the addendum circle: $S_e = 0.51\sqrt{m}$.

Analysis of the above dependencies and diagrams allows us to form several recommendations:

- shapers with a large number of teeth allow for a given module large values of the basic distances and therefore are more expedient than shapers with a smaller number of teeth. So, for example, for ($h_a^* + c^* = 1.25$) and m_0 = 3.5 mm, the cutters with z_0 = 28 (diameter d_0 = 100 mm) admit the coefficient of the basic distance $\varepsilon = A/m_0 = 4.28$, while the shaper cutters of the same module with z_0 = 22 (diameter d_0 = 75 mm) – only $\varepsilon = 2.85$.

- shapers with a head height coefficient $h_a^* + c^* = 1.25$ allow larger values of the basic distance than shapers with coefficient $h_a^* + c^* = 1.3$.

10. Determination of the new shaper dimensions (Fig. 3.4, section II-II).

10.1. Tooth head height h_{a0}

$$h_{a0} = h_{a0I} + A \cdot \text{tg}\alpha_{tp}.$$

10.2. Tooth root height h_{f0}

$$h_{f0} = h_{f0I} - A \cdot \text{tg}\alpha_{tp}.$$

10.3. The addendum diameter of the new shaper $\underline{d}_{a0}$

$$d_{a0} = d_{a0I} + 2A \cdot \text{tg}\alpha_{tp}.$$

10.4. The dedendum diameter of the new shaper d_{f0}

$$d_{f0} = d_0 - 2 \cdot h_{f0}.$$

10.5. Thickness of teeth along an arc of pitch circle S_0 (S'_r)

$$S_0 = S_{0I} + 2A \cdot \text{tg}\alpha_l$$

Counting according to clauses 10.1...10.5 with an accuracy of 0.001 are performed.

3.3. Checking the structural elements of the shaper

After determining all the parameters of the shaper, a check should be made for the absence of interference (punching, jamming, intersection of the profiles) of the teeth profiles of the cut wheel z_1 with a paired (conjugating) wheel z_2 = 120 teeth and for the absence of undercutting the teeth of the cut wheel by the shaper.

3.3.1. Checking the shaper for the absence of interference on the transition curves of the gear wheels

This check is performed at the maximum positive displacement of the basic rack contour, i.e. for the new shaper. With the selected value of displacement *A*, a thickening is obtained at the teeth roots of the wheels cut by the shaper. In this case, the profile is outlined not by the involute, but by a certain transition curve. In this case, when the wheels engagement, the intersection of the wheel teeth profile can occur, which leads to an uneven run with high noise and rapid wear of the gear wheels [75-77]. This intersection is associated with the ratio of the working section length *K'L* and the length of the involute section *KL*, cut with a shaper (Fig. 3.8).

The active section on the shaper-cut wheel z_1 will be the longer, the more the number of teeth the paired wheel z_2 will have. In this case, the length of the inactive section will change in the opposite direction.

Therefore, for a certain number of wheel teeth z_2, the length of the working section *K'L* will be greater than the length of the involute section *KL*. In this case, the engagement will be carried out partially and in the area *KK'* corresponding to the thickening of the root and having the shape of an elongated epicycloid. In case of significant, the thickness of the transition curve will lead to the intersection of the wheels tooth profiles and to the engagement of the teeth tips, which creates rapid wear of the teeth and irregular running with high noise. With a large deviation from the correct engagement, even pinching and breakage of the teeth can occur.

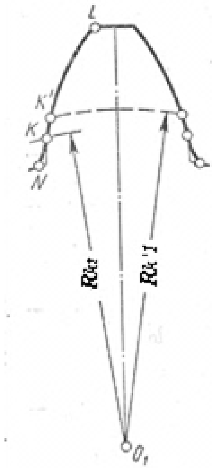


Fig. 3.8. The layout of the transition curve

If it is required to cut a pair of wheels interlocking with each other, then the shaper for this should be chosen so that it gives transition curves on the teeth of these wheels that are lower in height than the inactive sections of the profiles, i.e. so that $K'N \geq KN$. There will be no crossings of profiles when this condition is as follows: $R_{K'1} \geq R_{Kt}$ is expressed.

Analytically, the above condition is met if the inequality is met:

$$(z_1+z_2)\cdot tg\alpha - z_2\cdot tg\alpha_{e2} \geq (z_1+z_0)\cdot tg\alpha_{10} - z_0\cdot tg\alpha_{a0},$$

where α_{e2} is the pressure angle of the involute on the addendum circle of the wheel z_2

$$\cos \alpha_{e2} = r_{b2} / R_{e2},$$

where $r_{b2} = 0.5\, m\, z_2 \cos\alpha$ – radius of the wheel base circle z_2;
$R_{e2} = 0.5\text{m}\cdot(z_2+2)$ – the radius of the wheel addendum circle z_2;
α_{a0} – pressure angle of the involute at the teeth apexes of the new shaper, which is determined by the formula:

$$\cos\alpha_{a0} = \frac{z_0 \cdot \cos\alpha}{2 \cdot \left(\frac{z_0}{2} + \xi_t \operatorname{tg}\alpha_{tp} + h_a' + c' \right)},$$

where α_{10} – the angle of engagement of the new shaper with the cut wheel, determined by the formula (3.1)

$$\operatorname{inv} \alpha_{10} = \operatorname{inv} \alpha + 2\cdot(\xi_1+\xi_t)\cdot \operatorname{tg} \alpha/(z_1+z_0), \qquad (3.1)$$

where ξ_1 – a shift of the basic contour of the wheel z_1

The values of inv α_x are given in the literature.

Thus, the transition curve obtained on the cut wheel z_1 must be equal to or less than the inactive section *KN* (Fig. 3.8) obtained on the same wheel when engagement to the paired wheel z_2.

Standard spur cutters are designed mainly for cutting gears with a range of teeth numbers 17...120 and for a maximum pair of numbers z_1+z_2 = 120+120 = 240.

3.3.2. Checking the shaper's tooth for sharpness

One of the limitations when choosing the value of the basic distance of the shaper *A* is the inadmissibility of the sharpening of the shaper teeth tops, which can occur at significant values of *A* and which can lead to rapid wear of the tooth tip during cutting. To avoid this, the shaper tooth must have a certain minimum value of $S_{a0\min}$ around the addendum circle.

When checking, first, the angle of the profile pressure on the addendum diameter of the shaper α_{a0} is calculated

$$\cos \alpha_{a0} = d_{b0}/d_{a0}.$$

In this case, the thickness of the tooth on the addendum diameter S_{a0} (S_e, Fig. 3.6) in section II-II is calculated according to the following relationship:

$$S_{a0} = d_{a0}\cdot[(S_0/d_0)+\text{inv } \alpha_0 - \text{inv } \alpha_{a0}].$$

The S_{a0} value should not be less than the $S_{a0\min}$ values presented in Table. 3.6.

Table 3.6

Minimum tooth thickness $S_{a0\min}$

Module m_0	1…1.5	1.75…2.5	2.75…4.5	4.75…5.0	5.5…6.0
Minimum thickness $S_{a0\min}$	0.5	0.8	1.0	1.3	1.5

If the condition $S_{a0} \geq S_{a0\min}$ is not met, then the value of A in item 10 should be reduced and S_{a0} should be calculated again.

3.3.3. Checking the shaper for the absence of undercutting the wheel teeth root

This check is done for the maximum sharpened tooth (section X-X, Fig. 3.9), which is not undercutting under the condition:

$$R'_{a0} \leq \sqrt{A'_{10}\sin\alpha'_{10}{}^2 + r_{b0}^2} \ ,$$

where R'_{a0} – radius of the addendum circle of the maximum shaper:

$$R'_{a0} = R_{a0} - 2\,A\,\mathrm{tg}\alpha_{tp},$$

A'_{10} – the distance between the axes of the grinding shaper and the machined wheel z_1

$$A'_{10} = 0.5 \cdot m \cdot (z_0 + z_1) \cdot \cos\alpha / \cos\alpha'_{10}\ , \qquad (3.2)$$

where α'_{10} – the angle of engagement of the grinding shaper with the machined wheel:

$$\mathrm{inv}\ \alpha'_{10} = (2 \cdot \mathrm{tg}\alpha \cdot (\xi_1 + \xi'_t)/(z_0 + z_1)) + \mathrm{inv}\alpha,$$

where $\xi'_t = (H - A - (3\ldots\ 5)) \cdot \mathrm{tg}\alpha_{tp}/m$;

r_{b0} – radius of the basic circle of the shaper:

$$r_{b0} = 0.5\ m\ z_0 \cos\alpha.$$

The necessary conditions for the absence of undercutting the wheel tooth root indicate that the limit wear of the shaper should be less than the selected one.

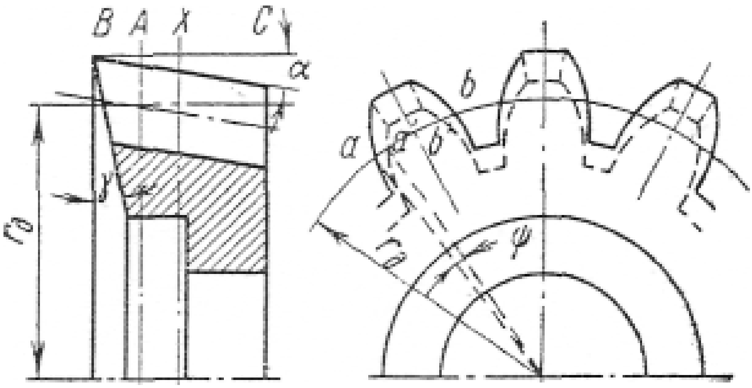


Fig. 3.9. Shaper cross-sections

3.3.4. Checking the shaper's tooth for the absence of undercutting the teeth head wheel (with the maximum wear shaper)

As the shaper grinds, the non-involute area at the shaper's tooth increases. This section of the tooth, under some conditions, can cut corners at the heads of the teeth of the wheel [78-80]. There is no cutting off the wheel teeth heads if the following conditions are met:

$$R_{a1} \leq \sqrt{\left(A'_{10} \cdot \sin\alpha'_{10}\right)^2 + r_{b1}^2}, \tag{3.3}$$

where R_{a1} is the radius of the addendum circle of the wheel z_1:

$$R_{a1} = 0.5m\left(z_1 + 2h^*_{a1}\right),$$

where r_{b1} – radius of the base circle of the wheel z_1;

$r_{b1} = 0.5\ m\ z_1 \cos\alpha$.

If the check shows that the inequality (3.3) and the corners are cut off at the wheel teeth head, then it is necessary to reduce the amount of shaper grinding is not observed.

3.4. Graphical check of the shaper structural elements

3.4.1. Checking for the absence of interference on the transition curves

We construct the engagement of the wheel z_1 with the shaper on one side and with the paired wheel z_2 on the other (Fig. 3.10).

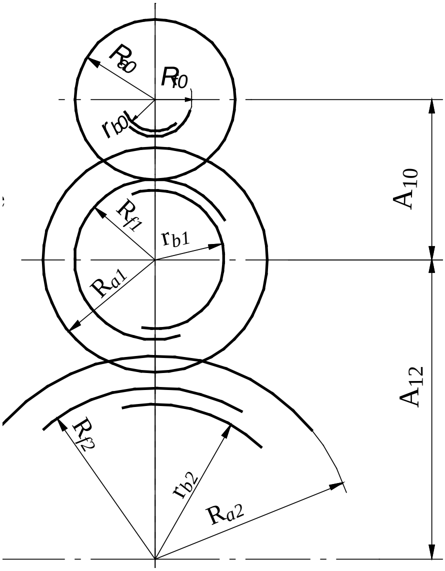


Fig. 3.10. Graphical check for interference

For clarity and simplicity, these engagements are shown in one figure. When constructing a diagram, it is necessary to accurately lay off the segments corresponding to the previously calculated values of A_{10} and A_{12}. Here A_{10} is the distance between the axes of the shaper and the wheel z_1, determined similarly to expression (3.2). In this expression, instead of the engagement angle of the undercutting shaper α'_{10}, the angle of engagement of the new shaper α_{10}, determined by dependence (3.1), is taken into account. The distance A_{12} between the gears is defined as:

$$A_{12} = 0.5 \cdot m \cdot (z_1 + z_2).$$

3.4.2. Check for the absence of undercutting teeth root of the cut wheel z_1

The check is carried out for a completely undercutting shaper (Fig. 3.11). The construction is carried out in the following sequence:

a) the axes position of the shaper and the wheel z_1 is outlined, the distance between the axes of which is equal to the value A'_{10} (3.2);

b) a line of engagement *MN* is drawn, which tangent to the base circles of the shaper and the wheel z_1;

c) an addendum circle of the shaper with radius R'_{a0} is drawn.

Checking for the absence of undercutting of the roots is carried out using the condition: $O_0M > R'_{a0}$. If the considered condition is not met, this means that the grindability limit of the shaper must be less than the accepted value.

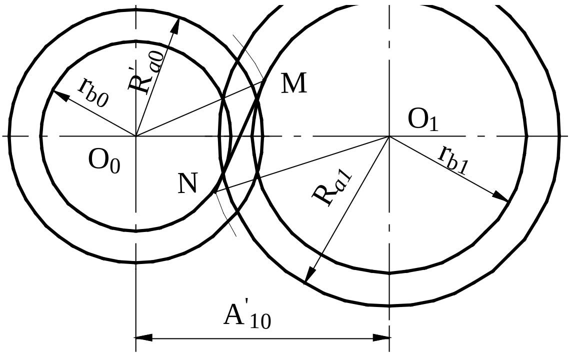


Fig. 3.11. Graphical check for undercutting

3.4.3. Check for the absence of the teeth heads undercutting of the cut wheel z_1

The check is carried out for a completely undercutting shaper

(Fig. 3.11), by comparing the values of the radius of the addendum circle of the cut wheel R_{a1} and the segment connecting its centre and the beginning of the engagement line NO_1: $NO_1 > R_{a1}$.

Failure to comply with this condition determines that the maximum permissible wear of the shaper should be less than the previously selected one.

4. NUMERICAL CALCULATION OF A SPUR-TYPE DISC SHAPER FOR CUTTING GEAR WHEELS

Initial data:

- module of the gear wheel GW) being cut: $m = 5$;
- number of GW teeth: $z_1 = 20$;
- number of teeth of the paired gear wheel: $z_2 = 30$;
- angle of the main profile: $\alpha = 20^0$;
- shift coefficient: $\xi_1 = \xi_2 = 0$;
- degree of GW accuracy: 7-D;
- material of processed wheels: steel 50;
- gear shaping machine: 5M14.

4.1. Determination of additional technological parameters of the gear wheel

Pitch circle diameters:

$$d_1 = m\, z_1 = 5\ 20 = 100 \text{ mm};$$

$$d_2 = m\, z_2 = 5\ 30 = 150 \text{ mm}.$$

Diameters of the addendum circles:

$$d_{a1} = m\,(z_1+2) = 5\ (20+2) = 110 \text{ mm};$$

$$d_{a2} = m\,(z_2+2) = 5\ (30+2) = 160 \text{ mm}.$$

Dedendum circle diameters:

$$d_{f1} = d_1–2.5\ m = 100–2.5\ 5 = 87.5 \text{ mm};$$

$$d_{f2} = d_2–2.5\ \text{m} = 150–2.5\ 5 = 137.5 \text{ mm}.$$

Diameters of the basic circles:

$$d_{b1} = d_1 \cos\alpha = 100\ 0.9397 = 93.9693 \text{ mm};$$

$$d_{b2} = d_2 \cos\alpha = 150\ 0.9397 = 140.9539 \text{ mm}.$$

Tooth thickness along the pitch circle:

$$S_1 = S_2 = 0.5\ \pi\ m = 0.5\ 3.1416\ 5 = 7.854 \text{ mm.}$$

Center-to-center transmission distance:

$$A_{12} = 0.5\ m\ (z_1 + z_2) = 125 \text{ mm.}$$

4.2. Calculation of a spur-type shaper

1. Shaper module m_0

$$m_0 = m = 5 \text{ mm.}$$

2. Nominal pitch circle diameter d_{0n}. According to the passport data of the machine model 5M14 (Table 3.2), we take: d_{0n} = 80 mm.

3. The number of shaper teeth z_0:

$$z_0 = d_{0n}/\text{m} = 80/5 = 16.$$

4. Pitch circle diameter d_0:

$$d_0 = m\ z_0 = 5\ 16 = 80 \text{ mm.}$$

5. The diameter of the theoretical base circle d_{b0}:

$$d_{b0} = d_0 \cos\alpha_0 = 80 \cos 20^0 = 75.175 \text{ mm.}$$

6. Back angle at apex α_{tp} and front angle γ. This shaper is finished (accuracy class *A*), therefore, the front and back angles take the recommended values: $\gamma = 5^0$; $\alpha_{tp} = 6^0$.

7. Profile angle of the shaper α_0

$$\alpha_0 = arctg\frac{tg\alpha}{1 - tg\alpha_{tp} tg\gamma} = arctg\frac{tg20^0}{1 - tg6^0\, tg5^0} = 20^0 10' 14.5''.$$

8. Lateral clearance angle α_l:

$$tg\alpha_l = tg\alpha_{tp} \cdot tg\alpha_0 \rightarrow \alpha_l = 2^0 12'40''.$$

9. Parameters of the shaper in the basic section I - I (Fig. 3.4)

9.1. Shaper outer diameter d_{a0I}

$$d_{a0I} = d_0 + d_1 - d_{f1} = 80+100–87.5 = 92.5 \text{ мм}.$$

9.2. Shaper teeth thickness S_{0I} (Fig. 3. 6) on the pitch circle

$$S_{0I} = 0.5\cdot\pi\cdot m_0 + \Delta S_0 = 0.5\cdot 3.1416\cdot 5+0.175 = 8.02898 \text{ мм}.$$

9.3. Height of the head and root of the tooth h_{a0I}, h_{f0I}:

$$h_{a0I} = h_{f0I} = 1.3\cdot m_0 = 1.3\cdot 5 = 6.5 \text{ мм}.$$

9.4. Basic distance A (Fig. 3.4). To determine the value of A, we determine the minimum permissible thickness of the teeth of the shaper along the addendum circle S_e (Fig. 6). For the shaper module m_0 = 5 mm (Table 3.5).

$$S_e = 0.25\cdot m_0 = 1.25 \text{ мм}.$$

Expressing the value of S_e as a fraction of the modulus, we obtain the coefficient $\sigma_e\left(S'_e\right) = 0.25$.

The coefficient of displacement of the initial section ξ_t is found according to the diagram in Fig. 3.7, b at $\sigma_e = 0.25;\ z = 16:\ \xi_t \approx 0.05$.

You can roughly determine the shift coefficient analytically:

$$\xi_t \approx 0{,}01\cdot z_0 - 0.1 = 0.01\cdot 16 - 0.1 = 0.06.$$

Then the basic distance A (mm) is determined by the formula:

$$A = \frac{\xi_t \cdot m_0}{tg\alpha_{tp}} = \frac{0.05 \cdot m}{0.105} = 2.38.$$

Following GOST 9323 - 79, the shift coefficient of the basic contour $X_0(\xi_t)$ takes the value X_0 = 0.06, and the distance of the basic section from the front surface is A = 2.8. Hub width b_1 = 8 mm; shaper height B (H) = 17 mm.

10. Determination of the dimensions of the new shaper (Fig. 3.4, section II-II).

10.1. Tooth head height h_{a0}

$$h_{a0} = h_{a0I}+A\cdot \text{tg}\alpha_{tp} = 6.5+2.8\cdot 0.105 = 6.794 \text{ мм.}$$

10.2. Tooth root height h_{f0}

$$h_{f0} = h_{f0I} - A\cdot \text{tg}\alpha_{tp} = 6.5–2.8\cdot 0.105 = 6.206 \text{ мм.}$$

10.3. The addendum diameter of the new shaper d_{a0}

$$d_{a0} = d_{a0\text{I}}+2\cdot A\cdot \text{tg } \alpha_{tp} = 92.5+2\cdot 2.8\cdot 0.105 = 93.088 \text{ мм}$$

10.4. The diameter of the deddendum circle of the shaper d_{f0}

$$d_{a0} = d_{a0\text{I}}+2\cdot A\cdot \text{tg } \alpha_{tp} = 92.5+2\cdot 2.8\cdot 0.105 = 93.088 \text{ мм}$$

10.5. Thickness of teeth along an arc of pitch circle S_0 (S_r')

$$S_0 = S_{0\text{I}}+2\cdot A\cdot \text{tg } \alpha_l = 8.02898+2\cdot 2.8\cdot 0.105 = 8.61698 \text{ мм.}$$

4.3. Checking calculations of the shaper

1. In the absence of interference

Let us determine the pressure angle of the involute α_{e2} on the wheel addendum circle z_2:

$$\alpha_{e2} = \arccos (r_{b2}/R_{e2}) = \arccos (70.4769/80) = 28.241615^0.$$

Let us determine the pressure angle of the involute α_{a0} on the shaper addendum circle:

$$\cos\alpha_{a0} = \frac{z_0 \cdot \cos\alpha}{2 \cdot \left(\frac{z_0}{2} + \xi_t \operatorname{tg}\alpha_{tp} + h_a^* + c^* \right)} = \frac{16 \cdot \cos 20^0}{2 \cdot (8 + 0.06 \cdot tg6^0 + 1 + 0.3)} = 0.807791;$$

$$\alpha_{a0} = 36.1194350.$$

Let us determine the angle of engagement α_{10} of the new shaper with the cut wheel:

$$\text{inv } \alpha_{10} = \text{inv } \alpha + 2\cdot(\xi_1+\xi_t)\cdot \operatorname{tg} \alpha/(z_1+z_0) = \text{inv } 20^0 +$$
$$+2\cdot 0.06\cdot \operatorname{tg}20^0/(20+16) = 0.016117;$$
$$\alpha_{10} = 20.508333^0.$$

The analytical condition calculated for the above initial data is satisfied, therefore, there is no interference phenomenon on the transition curves of the gears:

$$(z_1+z_2)\cdot\operatorname{tg}\alpha - z_2\cdot\operatorname{tg}\alpha_{e2} \geq (z_1+z_0)\operatorname{tg}\alpha_{10} - z_0\cdot\operatorname{tg}\alpha_{a0};$$
$$(20+30)\cdot\operatorname{tg}20^0 - 30\cdot\operatorname{tg}28.241615^0 \geq (20+16)\cdot\operatorname{tg}20.508333^0 - 16\cdot\operatorname{tg} 6.119435^0;$$
$$2.084588 > 1.790101.$$

If this condition is violated, you must:

- increase the tooth root height of the wheel by (0.05 ... 0.15) *m*;
- increase the number of teeth of the shaper or decrease the value of the given section shift.

2. Check for the inadmissibility of sharpening of the shaper teeth tips is performed:

$$S_{a0} = d_{a0}\cdot[(S_0/d_0) + \text{inv } \alpha_0 - \text{inv } \alpha_{a0}] \geq S_{a0\,\min};$$
$$S_{a0} = 93.088\cdot[(8.61698/80) + \text{inv } 20.170694 - \text{inv } 36.119435^0] > 1.3;$$
$$2.20398 > 1.3.$$

3. Check for the lack of undercutting the teeth root of the wheel.

Let's define:

- coefficient of displacement of the shaper basic profile ξ'_t

$$\xi'_t = (H – A – 3)\cdot tg\alpha_{tp}/m = (17–2.8–3)\cdot tg\ 6^0/5 = 0.235.$$

- the angle of engagement of the wear shaper with the cut wheel α'_{10}:

$$inv\ \alpha'_{10} = (2\cdot tg\alpha\cdot(\xi_1+\xi'_t)/(z_0+z_1))+inv\alpha = (2\cdot tg20\cdot 0.235/(16+20))+0.014904 = 0.019656;$$

$$\alpha'_{10} = 21.856666^0.$$

- the distance between the axes of the wear shaper and the machined wheel z_1:

$$A'_{10} = 0.5\cdot m\cdot(z_0+z_1)\cdot\cos\alpha/\cos\alpha'_{10} = 0.5\cdot 5\cdot(16+20)\cdot\cos 20^0/\cos 21.856666^0 = 91.1224\ \text{mm}.$$

- the radius of the addendum circle of the maximum undercutting shaper R'_{a0}:

$$R'_{a0} = R_{a0} – 2\cdot A\cdot tg\alpha_{tp} = 0.5\cdot 93.088–2\cdot 2.8\cdot tg\ 6^0 = 92.499\ \text{mm}.$$

For the maximally undercutting tooth (section X-X, Fig. 3.9), the following condition is fulfilled:

$$R'_{a0} \le \sqrt{(A'_{10}\sin\alpha'_{10})^2 + r_{b0}^2}\ ;$$

$$45.955 < \sqrt{(91.1224\cdot\sin 21.856666)^2 + 61.080021^2} = 69.868.$$

4. Checking the shaper tooth for the absence of shearing off the head of the teeth of the wheel z_1

The radius of the circle of the protrusions R_{a1} of the wheel z_1 is

$$R_{a1} = 0.5 \cdot m \cdot (z_1 + 2 \cdot h^*_{a1}) = 0.5 \cdot 5 \cdot (20+2) = 55 \text{ мм.}$$

The check condition for the absence of shearing is fulfilled

$$R_{a1} \leq \sqrt{\left(A'_{10} \cdot \sin\alpha'_{10}\right)^2 + r_{b1}^2} = \sqrt{\left(91.1224 \cdot \sin 21.85666\right)^2 + 46.98465^2} \text{ ;}$$

$$55 < 57.951.$$

Otherwise, when cutting off the corners at the heads of the teeth of the wheel can occur, it is necessary to reduce the amount of shaper stitching.

A comprehensive check of the structural elements of the shaper showed the operability of the designed tool.

5. DESIGNING A SHAPER-TYPE GEAR CUTTER IN THE "KOMPAS" CAD SYSTEM

5.1. Design library "Shaper-type gear cutter"

The library operates in the environment of the KOMPAS system and provides the design of involute shaper gear cutters (SGC) of the middle module (from 1.0 to 12.0 mm) for the following types [81, 82]:

1) disc spur teeth (module up to 12 mm);

2) disc helical teeth (module up to 7 mm);

3) deep counterbore-type (module up to 9 mm);

4) shank-type spur (module up to 4 mm);

5) shank-type helical (module up to 4 mm).

The system can design both non-standard and selection from the database of standard SGC following GOST 9323-79.

In the design process, the following tasks are solved:

- calculation of SGC geometrical parameters;
- formation of values of accuracy indicators and technical requirements depending on the degree of the cut wheel accuracy;
- formation of an SGC working drawing;
- building an SGC three-dimensional model.

The calculation results can be displayed in MS Excel.

The SGC working drawing is formed using the KOMPAS-GRAFIK drawing-graphic editor, the three-dimensional model is created using the commands of the KOMPAS-3D three-dimensional solid design system. Automatically received graphic documents can be further edited using the usual KOMPAS tooling.

5.2. Setting the initial parameters of the gear

The input of the initial data for the SGC design is carried out in the dialogue mode (Fig.5.1)

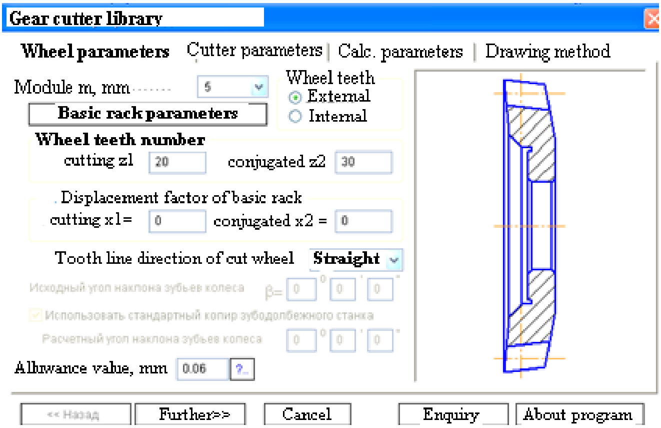


Fig. 5.1. Gear parameters

1. At the first stage, the initial parameters of the gears being cut and conjugated with it are set:

- module *m* (mm);
- type of gear teeth being cut (external or internal);
- parameters of the basic contour of gear wheels;
- number of wheel teeth (being cut z_1 and conjugate z_2);
- shift coefficients of the basic wheel contour (x_1 and x_2);
- inclination angle of the teeth β;
- direction of the line of teeth;
- allowance (mm).

At this stage is considered the allowance that must be left after machining the wheel by SGC. The value of allowance is the additional increase in tooth thickness that must be obtained after machining the wheel with SGC.

If SGC machining is the final operation, then the value of allowance is equal to the smallest deviation in the tooth thickness of the wheel being cut required to form a guaranteed lateral clearance in the gearing. In this case, the value of allowance depends on the accuracy degree of the wheel and the type of side clearance and is selected by the data of GOST 1643-81.

For standard SGC with helical teeth, the tooth angle from the database is automatically selected.

For non-standard SGC, you can use the standard helical tracer of the gear-shaping machine if the angle of the teeth is $15^0 \pm 0.5^0$ or $23^0 \pm 0.5^0$. For 15^0 – the pitch of the standard copier is 1198 mm, for 23^0 – 751.96 mm.

The calculated tooth inclination angle is the actual tooth inclination angle of the wheel obtained from the design. It is equal to the SGC angle of inclination of the helical-type teeth. The calculated angle of teeth inclination may differ from the original value if using a standard helical tracer or a standard SGC from the database.

2. At the second design stage, the SGC initial parameters are set (Fig. 5.2)

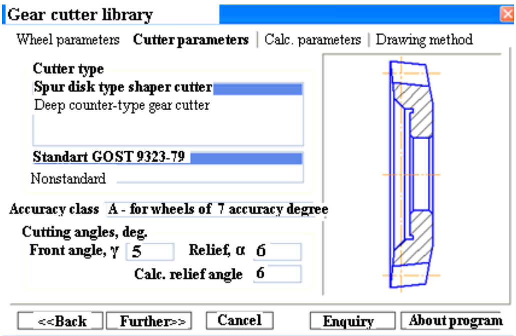


Fig. 5.2. SGC-parameters

In the *Shaper Type* list, only those tool types are offered for selection that is suitable for the original gear parameters.

The calculation of both a non-standard SGC and a selection from the database of a standard SGC following GOST 9323-97 has been implemented [83, 84]. When a standard SGC is selected, the entry fields for the cutter angles become unavailable, and the back and front rake angles of the SGC automatically take the recommended values.

3. At the third design stage (*Calculated parameters*) a list of SGC options is displayed, obtained as a result of the calculation (for non-standard cutters), or as a result of a database search for standard cutters (Fig. 5.3).

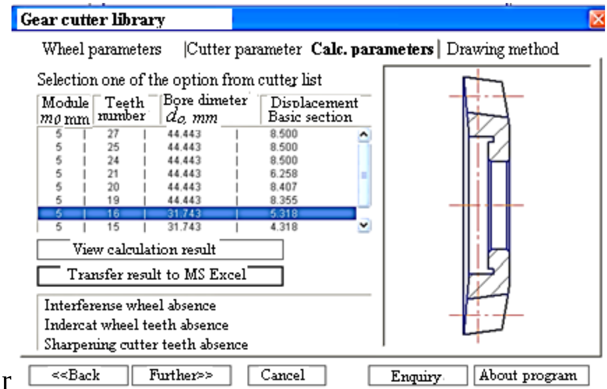
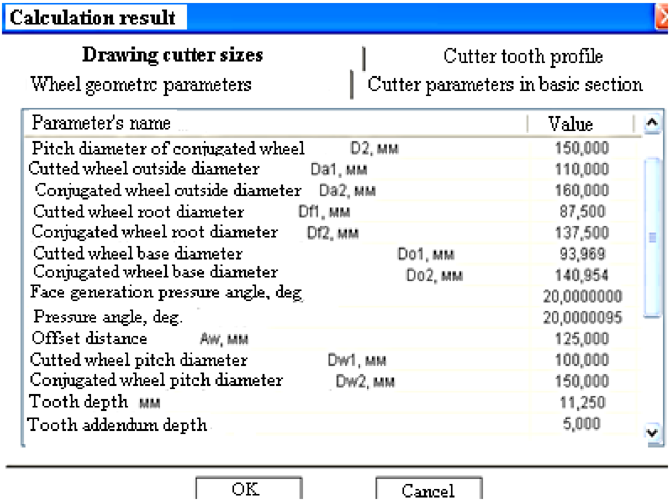
r 

Fig. 5.3. Calculated parameters of the SGC

The page contains the following buttons:

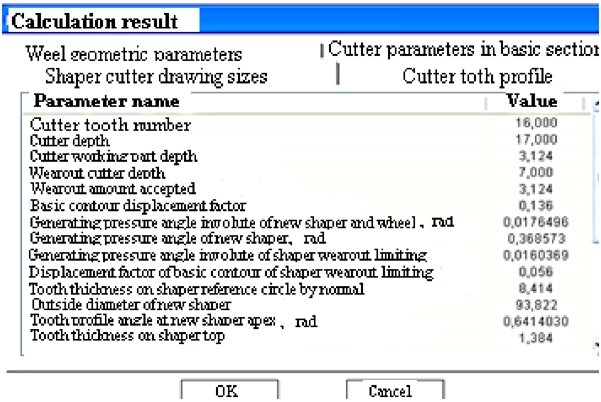
- to select a standard SGC from the database (the button is available only for standard cutters);
- to view the results of geometric calculations (Fig. 5.4);
- to display the calculation results in MS Excel (Fig. 5.5).

The page contains a field with notes, where the results of the check calculation for the suitability of this SGC for processing a gear wheel are displayed.



Parameter's name		Value
Pitch diameter of conjugated wheel	D2, мм	150,000
Cutted wheel outside diameter	Da1, мм	110,000
Conjugated wheel outside diameter	Da2, мм	160,000
Cutted wheel root diameter	Df1, мм	87,500
Conjugated wheel root diameter	Df2, мм	137,500
Cutted wheel base diameter	Do1, мм	93,969
Conjugated wheel base diameter	Do2, мм	140,954
Face generation pressure angle, deg		20,0000000
Pressure angle, deg.		20,0000095
Offset distance	Aw, мм	125,000
Cutted wheel pitch diameter	Dw1, мм	100,000
Conjugated wheel pitch diameter	Dw2, мм	150,000
Tooth depth мм		11,250
Tooth addendum depth		5,000

Fig. 5.4. Geometric parameters of gear wheels



Parameter name	Value
Cutter tooth number	16,000
Cutter depth	17,000
Cutter working part depth	3,124
Wearout cutter depth	7,000
Wearout amount accepted	3,124
Basic contour displacement factor	0,136
Generating pressure angle involute of new shaper and wheel , rad	0,0176496
Generating pressure angle of new shaper, rad	0,368573
Generating pressure angle involute of shaper wearout limiting	0,0160369
Displacement factor of basic contour of shaper wearout limiting	0,056
Tooth thickness on shaper reference circle by normal	8,414
Outside diameter of new shaper	93,822
Tooth profile angle at new shaper apex , rad	0,6414030
Tooth thickness on shaper top	1,384

Fig. 5.5. Calculation results: drawing dimensions

The numerical results of the calculation and the profile parameters of the SGC-tooth using the specialized program "Shaper-type gear cutter" are presented in Fig. 5.6 and Fig. 5.7 respectively.

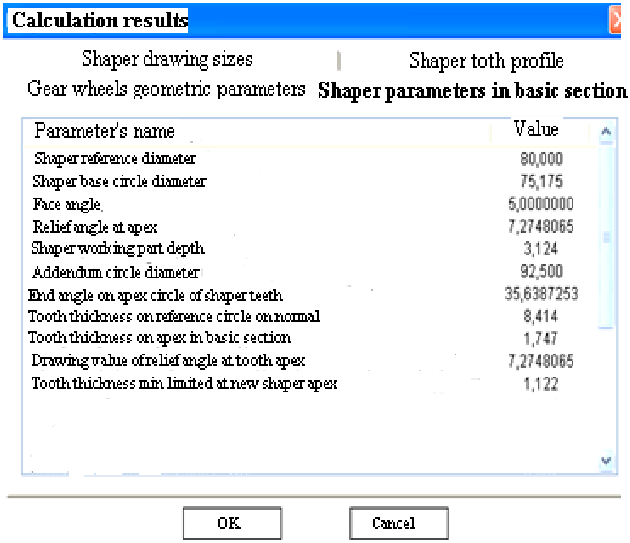


Fig. 5.6. Calculation results: SGC-parameters

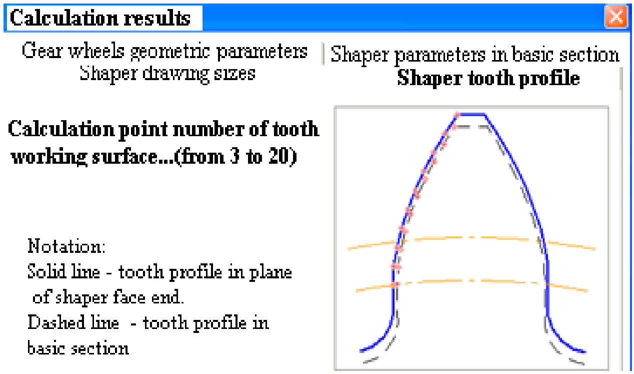
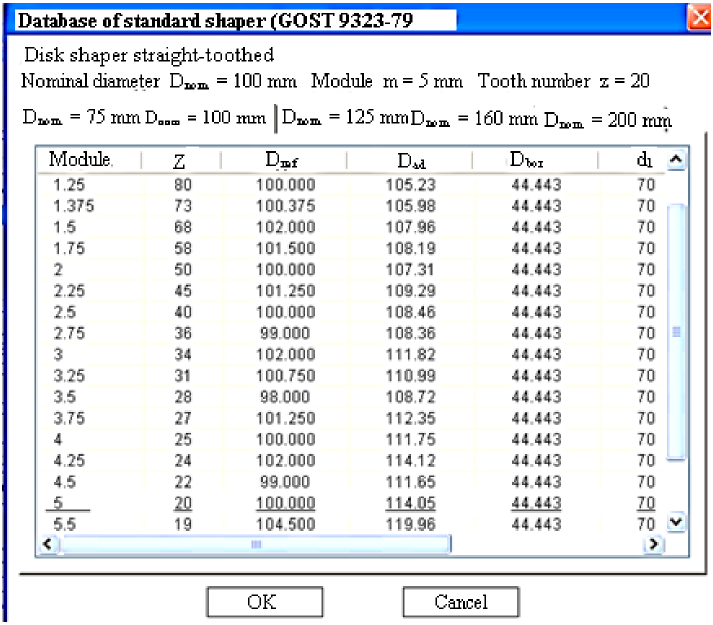


Fig. 5.7. Geometric calculation results

When constructing the profile of the SGC tooth, the involute section of the tooth-working surface is replaced by a Bezier curve. The number of calculated points on the working surface of the tooth affects the accuracy of drawing the involute line when constructing the tooth profile in the drawing [85-87]. The larger the tooth size (i.e. the larger the module), the more points you need to set to build a smooth tooth profile line.

You can select a standard cutter from the database by clicking the *Select standard cutter from database* button. In fig. 5.8 shows a database of disc-type shapers straight toothed. The dialogue panel has five tabs corresponding to different nominal SGC diameters.

If the SGC with the specified module does not exist, then a message is displayed that it is not found in the database.



Module	Z	D_{nf}	D_{ad}	D_{bz}	d_1
1.25	80	100.000	105.23	44.443	70
1.375	73	100.375	105.98	44.443	70
1.5	68	102.000	107.96	44.443	70
1.75	58	101.500	108.19	44.443	70
2	50	100.000	107.31	44.443	70
2.25	45	101.250	109.29	44.443	70
2.5	40	100.000	108.46	44.443	70
2.75	36	99.000	108.36	44.443	70
3	34	102.000	111.82	44.443	70
3.25	31	100.750	110.99	44.443	70
3.5	28	98.000	108.72	44.443	70
3.75	27	101.250	112.35	44.443	70
4	25	100.000	111.75	44.443	70
4.25	24	102.000	114.12	44.443	70
4.5	22	99.000	111.65	44.443	70
5	20	100.000	114.05	44.443	70
5.5	19	104.500	119.96	44.443	70

Fig. 5.8. Database of standard SGC

4. At the fourth stage, a method for visualizing the design results is set (Fig. 5.9). It is possible to create the following graphic documents: working drawing, 3D model, document with calculation results in .cdw

format. If the *Working drawing* (.cdw file) option is enabled, then the options for switching *View*, *Section*, *View/Section* become unavailable. In the working drawing, the SGC is created with certain views, the main projection of the cutter contains either a section for SGC with straight-toothed cutters or a half-section (*View/Section*) for a helical SGC.

If the *Working drawing* (.cdw file) option is disabled an SGC macro object will be created in the currently open drawing. In this case, view-switching options are available.

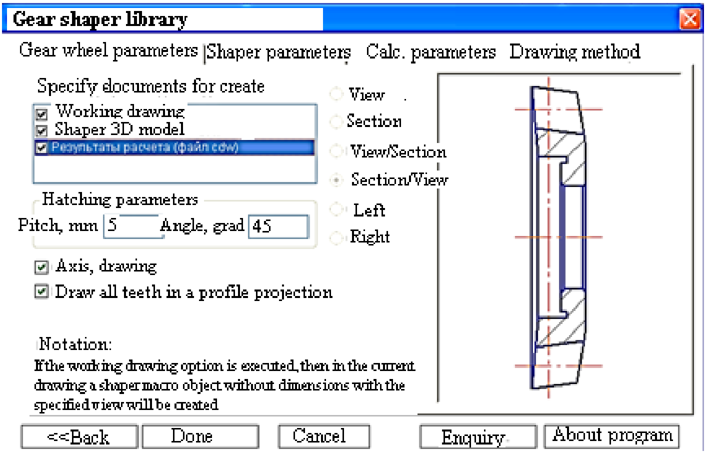


Fig. 5.9. The way to draw the SGC

5. Creation of a working drawing. A phantom of the tool drawing and a special control window will appear in the graphic document window of the KOMPAS system. The commands contained in this window allow you to edit the SGC parameters before fixing the drawing phantom. To call the required command, double-click on its name in the control window or select it from the context menu. When the phantom matches the desired image, you need to specify the insertion point of the phantom, and then the angle of its rotation. To abandon the drawing,

press the *Esc* key or call the "*Interrupt command*" command from the context menu.

The SGC-working drawing contains two of its projections with all the necessary dimensions, designations of roughness, deviations in the shape and location of surfaces, technical requirements, a table of parameters and remote elements containing the tooth profile.

The drawing on an A2 sheet is created. The drawing is almost finished form and in most cases requires minimal editing (filling in the title block, changing the sheet format for fine-module SGC is generated. With small dimensions of the tool, it is possible to overlay dimensional designations.

As a result of designing a spur-toothed SGC in the KOMPAS system, it three-dimensional model was obtained, shown in Fig. 5.10.

As a result of designing a spur-toothed shaper in the KOMPAS system, a three-dimensional shaper model was obtained, which is shown in Fig. 5.10.

A similar procedure for the SGC deep counterbore-type. Fig. 5.11 shows, the result of the design and 3D modelling of an SGC deep counterbore-type can be carried out.

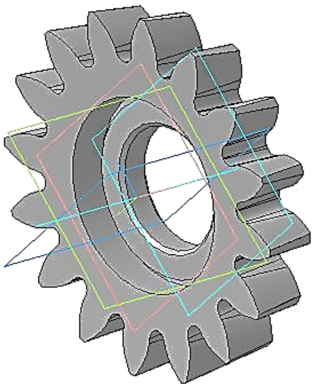


Fig. 5.10. 3D model of a gear-cutting shaper

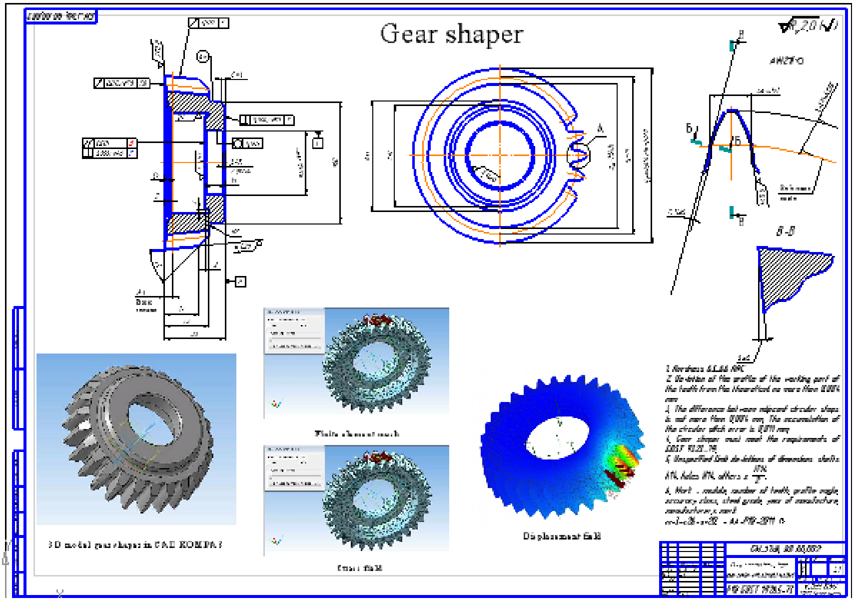


Fig. 5.11. The project of a gear-cutting shaper in a specialized application CAD KOMPAS

6. INTERLOCKING DISC MILLING CUTTER: DESIGN AND PARAMETRIC MODELING

6.1. General provisions

For cutting spur, helical and chevron gear wheels of the 9th and coarser degrees of accuracy (GOST 1643-81), disk (Fig. 6.1) and end-mill gear cutters (Fig. 6.2) are used [1].

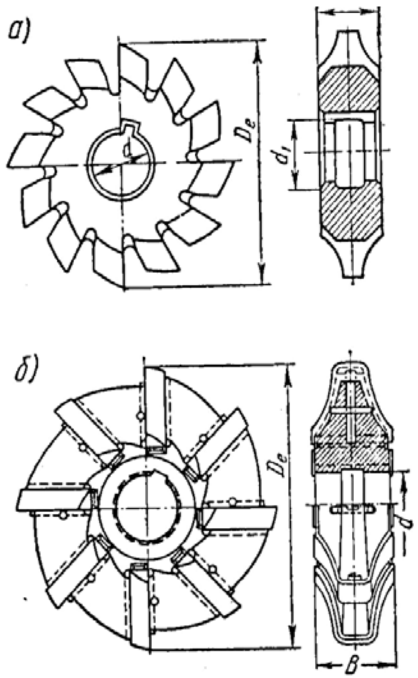


Fig. 6.1. Interlocking disk milling cutters: a – one-piece construction; b – built-up construction

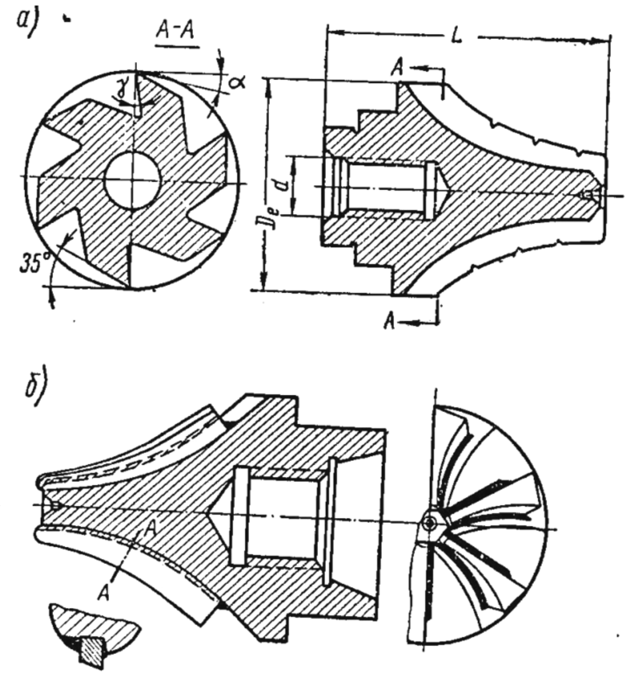


Fig. 6.2. End-mill gear cutter: a – one-piece construction;
b – with welded teeth construction

Interlocking Disk Milling Cutters (IDMC), which work mainly by the form-copying method, are shaped cutters with relieving teeth, the profile of which corresponds to the profile of the bottom land of the cut wheel [1, 2, 88]. They allow you to cut gear wheels on conventional milling machines, are widespread in individual, and repair production. At the same time, such milling cutters do not ensure the achievement of the degree of tooth cutting accuracy that can be obtained with the use of tools using the form-generating method. IDMC are roughing and finishing. Rough cutters are used for preliminary cutting of bottom land (BL) between the teeth of the wheels, and finishing cutters for fine milling bottom land.

External forms of IDMC are standardized (GOST 10996-64). Their sizes are as follows (Fig. 1): module – from 0.3 to 16; outer (addendum) diameter D_e = 40÷170 mm; mounting bore diameter *d* = 16÷40 mm; number of teeth *z* = 26÷10. Rough cutters with stepped teeth for more intensive processing can be made. IDMC for cutting gears with module *m* = 22÷45 mm and a diameter of over 100 mm are made with assembly plug-in teeth (Fig. 6.1, b). These cutters are manufactured with addendum diameter D_e = 245÷375 mm; mounting bore diameter *d* = 50÷60 mm and width *B* = 66÷130 mm (respectively). Most relief cutters are manufactured with a rake angle $\gamma = 0$ and an angle of inclination of the cutting edge $\lambda = 0$. The angles γ and λ, which are nonzero, complicate the calculation, manufacture and control of cutters, as well as during its regrinding; they introduce errors in the part profile, even if the new cutter provides accurate processing of the specified surface [89-91]. The regrinding of cutters along the front plane is carried out in such a way that the angles $\gamma = 0$ and $\lambda = 0$ remains unchanged, i.e. during regrinding, the radial position of the front surface is preserved. When regrinding, each time one of the cutting edges will be removed and a new edge identical to it will be found located in the axial plane of the cutter.

Each specific case of cutting the teeth of the product corresponds to a certain profile of the milling cutter, which depends on the module, the angle of engagement, the number of teeth of the wheel, the shift coefficient (for corrected wheels). The design of a gear rack intended for cutting a gear wheel is considered in Appendix A3.

IDMC as a set of 8 or 15 cutters is made. At the same time, a set of 8 cutters is recommended for cutting wheels with a module up to 8 mm. Each cutter from the set intended for cutting wheels with a certain number or group of numbers of teeth (Table 6.1)

Table 6.1

Selecting the cutter number

Cutter number	1	2	3	4	5	6	7	8
Milling cutter set	12…13 teeth	14…16	17…20	21…25	26…34	35..54	55…134	135, rack

An example of a conventional designation of a cutter with module 3 and No. 5: Mill *m*3×No. 5 GOST 10996-64.

6.2. Calculation of the profile of the IDMC for spur wheels with a straight tooth

The initial data for calculating the cutter are the parameters of the gear being cut:

- number of teeth – z;
- module – m;
- pressure angle – α_0;
- radii of the base and pitch circles – r_b and r (r_p);
- coefficient of the tooth head height – f;
- tooth thinning (guaranteed lateral clearance) – ΔS;
- shift coefficient of the original contour – ξ;
- thickness of the tooth along the pitch circle – s ($s = \pi \cdot m/2$).

The IDMC-tooth profile exactly matches the profile of the BL-wheel presented in Fig.6.3).

To determine the profile of the tooth, it is necessary to determine the BL profile of the wheel [44, 92]. This profile is divided into two sections: the working section, which lies between the addendum circle and the base circle; the non-working area of the tooth, which contoured along the transition curve.

The involute section profile in two ways can be defined: graphically and analytically.

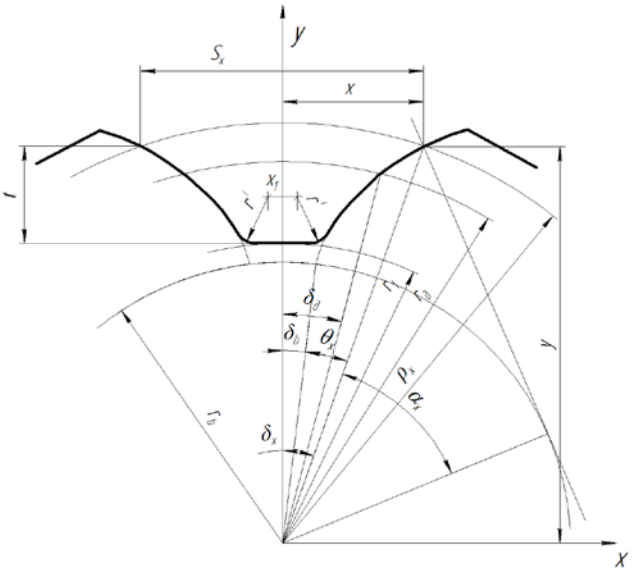


Fig. 6.3. Calculation of the profile involute part coordinates

Analytical method for determining the profile of the tooth involute section

Place the origin at the BL-center of the gear wheel (Fig. 6.3). The *OY*-axis is compatible with the middle of the BL-profile. Let's find the coordinates "X" and "Y" of any point of the milling cutter profile.

1. The radius of the base circle r_b (r_0) is calculated by the formula:

$$r_0 = \frac{mz}{2}\cos\alpha_0.$$

2. The angle of pressure at any point x, determined by the radius r_x, of the profile is calculated by the formula:

$$\cos\alpha_x = \frac{r_o}{r_x}.$$

The specifics of determining the pressure angle in Appendix A4 are considered.

The values of r_x are set in the range from $r_x = r_o$ to $r_x = R_e$ (R_e – radius of the addendum circle. The accuracy of calculating the angle of pressure α_x is 1". When using the tabular method for calculating the profile [3], several values of the unit radius of the vector ρ of the involute with the difference Δρ neighboring values $\Delta\rho = 0.002\, r_b$.

3. Half of the angular BL-width δ_d (in radians) on the pitch circle by the formula is determined:

$$\delta_d = \frac{\pi}{2z} - \frac{2\xi\, tg\alpha_0}{z} + \frac{\Delta s}{mz}.$$

When $r_d = m{\cdot}z/2$; $\xi = 0$; $\Delta s = 0$; $\delta_d = S_d/m{\cdot}z$. For uncorrected wheels ($\xi = 0$) δ_d can be negative.

4. Half of the BL-angular width δ_0 (in radians) on the base circle by the formula is determined:

$$\delta_0 = \delta_d - inv\alpha_0.$$

It is known from the involute equation:

$$\theta_x = tg\alpha_x - \alpha_x = inv\alpha_x.$$

5. Half of the BL-angular width δ_x (in radians) on a circle of radius r_x by the formula is determined:

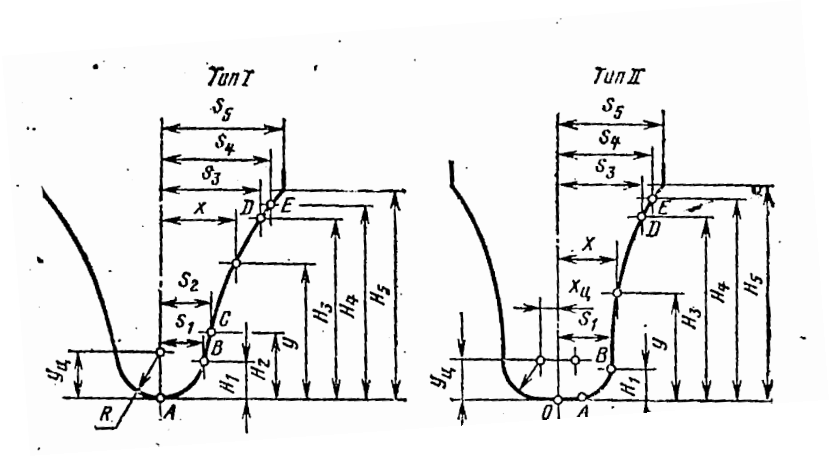
$$\delta_x = \delta_0 + inv\alpha_x.$$

The obtained value of the angle δ_x from radians to degrees is converted. The accuracy of the calculation is 1".

The coordinates of the profile points are determined (Fig. 6.4) with an accuracy of 0.001 mm as follows:

Abscissa $x = r_x \sin\delta_x$;

Ordinate $y = r_x \cos\delta_x$.



a b

Fig. 6.4. Tooth BL-profile coordinates: a – type I; b – type II

The dimensions of the non-involute profile part at the apex of the cutter tooth are taken from Table. [2, 18]. The tables show the values of the *x*- and *y*-coordinates for any point of the milling cutter profile, measured from the BL of the tooth. The table also presents the coordinates x_c of the rounding centres along the root of the tooth, the radius of curvature *R*, and then the points of coordinates *B*, *C*, *D*, *E* of the tooth profiles. Profile type I (Fig. 6.4, a) is intended for milling cutters No. 1-5. This profile consists of a circular arc *AB* of a straight-line segment *BC* and an involute *CDE*. Profile type II (Fig. 6.4, b) is designed for milling cutters No. 6 - 8. This profile consists of straight-line segments *OA* of circular arc *AB* and involute *BDE*. The value of the *x*-

and *y*-coordinates has given in the table for the module m = 100 mm. For other values of the modulus, the table values must be divided by 100 and multiplied by the modulus of the wheel being cut. According to the calculated coordinates, a gauge (template) and a counter-gauge are made to check the profile of the milling cutter being produced.

The transfer of the coordinate's origin from point *O* to the BL-center of the cut wheel (Fig. 6.3), which is necessary for constructing a gauge, is carried out taking into account the following expressions:

Ordinate $y_k = y – r_i$;

Abscissa $x_k = x$.

Here r_i is the radius of the BL-tooth, determined following GOST 16532-70

$$r_i = \frac{d - 2(f + c - \xi)m}{2},$$

where c – coefficient of the radial clearance; d – diameter of the pitch circle.

6. The maximum width of the BL-tooth profile, taking into account half of the angular horn-width δ_e, is determined with an accuracy of 0.001 by the formula:

$$S_e = 2r_e sin\delta_e;$$

$$\delta_e = (\delta_0 + inv\alpha_e) \cdot 57.29578,$$

where $\cos\alpha_e = r_0/r_e$;

$$r_e = \frac{d + 2(f + \xi)m}{2}.$$

The radius of the apexes r_e is determined taking into account the zero shift equalizing $\Delta y = 0$.

7. The width of the milling cutter *B* is calculated with an accuracy of 0.1 mm using the formula: $B = S_e + 2$ mm.

Cutter width B is recommended to be selected from the following row: 10, 12, 14, 15, 16, 18, 20, 22, 24, 25, 26, 28, 30, 32, 34, 35, 36, 38, 40 and further after 5 mm.

8. The cutter profile height H is also determined with an accuracy of 0.1 mm: $H = r_e - r_i$.

9. The clearance angle α_e on the cutter addendum diameter D_e (Fig. 6.2) is determined by the formula

$$tg\alpha_e = \frac{tg\alpha_l}{\sin\varepsilon},$$

where α_l – back angle on the lateral sides of the tooth;

ε – the angle of inclination of the profile at the addendum diameter of the cutter, which can be determined in a tabular way [2]. The counting accuracy is 5'.

10. The value of the relieving K (Fig. 6.5) is determined by the formula and rounded up to 0.5 mm:

$$K = \frac{\pi D_e}{z} tg\alpha_0 .$$

The values of the back clearance angle α at the apex of the tooth are $10^0...14^0$.

The value of second relieving K_1 is taken equal to (1.2...1.4)·K (Fig. 6.5).

When calculating the values of K and K_1, one should not forget that these are the values of the fall of the cams and for turning-relief and grinding-relief machines, these values are reduced to the normal range: 1.0; 1.5; 2.0; 2.5; 3.5; 4.5; 6; 7; 8; 9; 10.

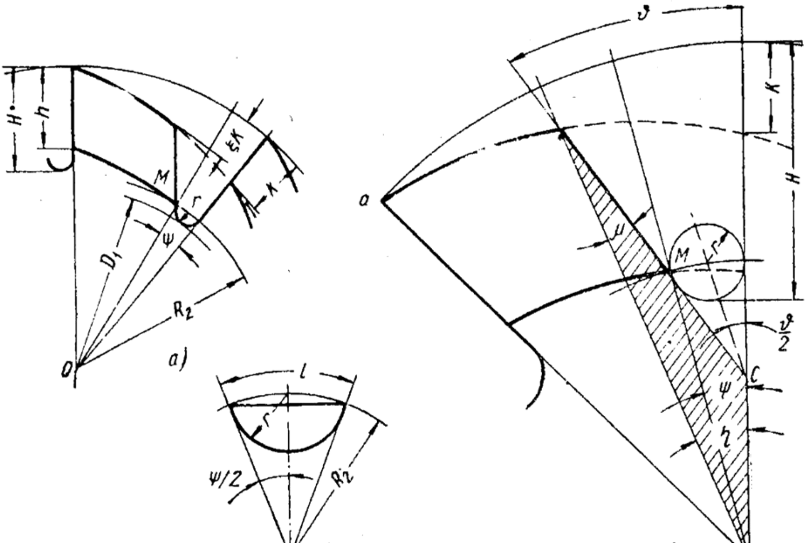


Fig. 6.5. Relieving cutter tooth

The overall dimensions and the number of teeth of IDMC-tool according to GOST 10996-64 or from reference literature are taken [4, 18].

6.3. Calculation of the IDMC-basic parameters

When designing special milling cutters, the main design parameters of the cutter – the addendum and mounting bore diameters and others are determined approximately [16, 18]. The selected solutions according to the dependencies recommended in the literature are checked.

1. Mounting bore diameter d_0, check according to the following ratio is carried out:

$$d_0 \leq 0{,}625(D - 2H).$$

The final value of the size of the mounting bore diameter of the cutter is taken as one of the largest nearest numerical values of the normal range of sizes of mounting bore diameters of the arbor-type cutting tool: 19, 22, 27, 32, 40, 50, determined by GOST 9472-70. After establishing the dimensions of the keyway t_k and b_k following GOST 8788-58 for the selected hole diameter, it is necessary to check the following condition:

$$0.5D_e - H - (t_k - \frac{d_0}{2}) \geq 0.3.$$

2. Undercut diameter D_1:

$$D_1 = d_0 + 1 \ldots 1.5 \text{ mm}.$$

3. The cutter profile height h is taken 1 ... 5 mm more than the depth of the BL-wheel:

$$h = 2.25m + 1 \ldots 1.5 \text{ mm}.$$

4. Chip groove depth H:

$$H = h + \frac{K + K_1}{2} + r,$$

where r – radius of curvature of the chip groove.

5. The number of teeth of the milling cutter z is approximately determined:

$$z = (1.8 \ldots 2.2)\frac{D_e}{H}.$$

The number of teeth of a cutter influences the size of the tooth and chip groove and is selected to provide sufficient tooth strength, space for the chips to escape when milling, and reserve for regrinding. The final number of teeth on a graphical calculation is based.

6. The root angle of the chip groove ε:

$$\varepsilon = \frac{360}{(4...8)\cdot z} + (16^0...22^0).$$

Usually, ε is taken from the range: 18^0, 22^0, 25^0, 30^0.

7. Radius of the chip groove curvature *r*:

$$r = \frac{\pi D}{10z}.$$

The radius of curvature *r* ranges from 1 to 5 mm. It must be selected in such a way as to ensure, within the chip groove, the removal of the relief cutter from the axis of the cutter during its relief.

8. Tooth width at base *C*: $C > 0.75H$.

9. Thickness of the cutter solid under the keyway *m*':

$$m' = (0.3...0.5)\ d.$$

10. The inclination angle of the straight bottom of the groove with a reinforced hub δ_1 (Fig. 6.6):

$$\delta_1 > \delta,$$

where δ – inclination angle of the straight line passing through the extreme points of the tooth profile.

The angle δ is determined graphically [18]. To give the tooth a stronger shape, the base of the root is outlined with a broken line (Fig. 6.6) corresponding to the tooth profile. Separate areas of the root base can be outlined by an arc of a circle, the radius of which is taken equal to the radius of the milling cutter that processes the chip groove.

11. Undercut length *b*:

To transmit the torque, relief-milling cutters usually have a longitudinal keyway.

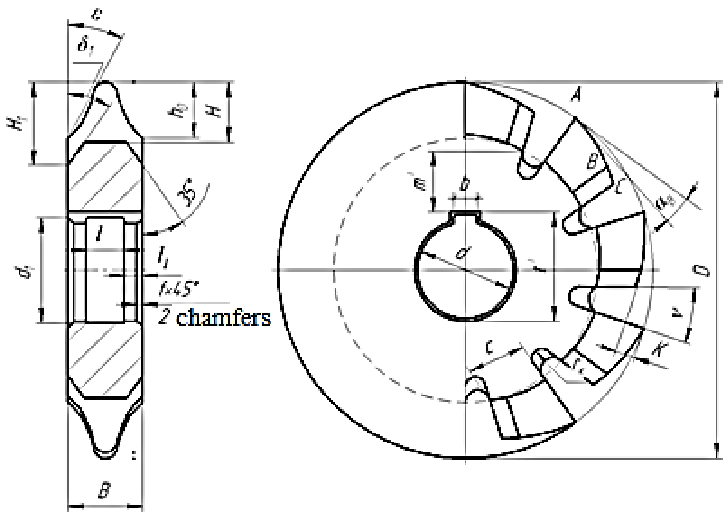


Fig. 6.6. The main parameters of the interlocking disk milling cutter

To facilitate grinding and ensure a better fit on the mandrel, the cutters are provided with an internal groove. The groove out diameter is 2...3 mm larger than the mandrel hole diameter. Holes from both ends are provided with chamfers at an angle of 45^0. The radius of the transition surfaces of the seating surface r_1 is taken in the range r_1 = 1...1.5 mm.

12. Final number of teeth *z*.

The final number of teeth is established based on a graphical calculation (Fig. 6.7). This value is determined by the fulfilment of the following conditions: ensuring the exit of the grinding wheel; the sufficiency of the grinding part length of the back surface and the strength of the cutter tooth [.

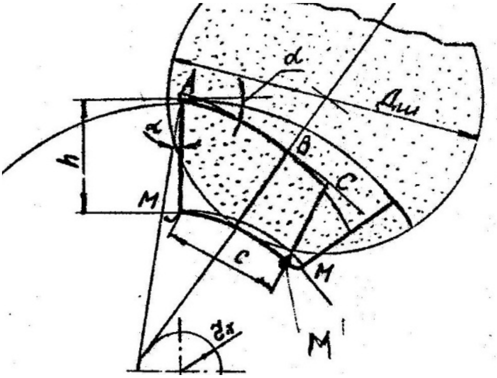


Fig. 6.7. Graphical calculation of the number of teeth

Based on the calculated parameters (3.1…3.12), the contour of the cutter teeth is drawn. The diameter of the grinding wheel D_{gr} should not be less than 60 mm and is calculated by the formula:

$$D_{gr} = 25+2h+5 \text{ (mm)}.$$

When constructing a tooth contour, draw an auxiliary circle with a radius r_x

$$r_x = 0.5D \sin\alpha.$$

The line ending the grinding part of the tooth and lying on the diameter of the grinding wheel in its extreme position will be tangent to this circle.

The ground part of the back surface of the cutter teeth must be at least 2/3 of the tooth length, and the grinding wheel in the end position must not come into contact with the next cutter tooth. To fulfil this condition, point M must be outside the working surface of the grinding wheel with diameter D_{gr} in its extreme position, and $\cup AB = 2 \cup BC$.

6.4. Parametric modelling of interlocking disc milling cutters in the APM WinMachine system

6.4.1. General provisions

In the drawing and graphic editor APM Graph, the possibility of the parametric definition of graphic objects [89, 93, 94].

It is known that complex-profile tools, such as Interlocking Disk Milling Cutter (IDMC) have several standard (unified) design solutions. These include, for example, the profile of a relief tooth with one- or double relief, an involute tooth contour, and others. The design of such unified forms becomes an order of magnitude more efficient using the parameterization toolkit. It allows you to automatically draw geometric objects if, after performing the necessary calculations, the latter were specified parametrically.

When working in this mode, the sequence of the executed commands and their attributes is automatically saved [95]. These attributes can be assigned appropriate names and the necessary numerical and functional relationships. Functional relationships can be completely arbitrary, i.e. described by arbitrary analytical functions. To define such functions, there is a special editor for the analysis and transformation of analytical data.

Several standard structural graphic elements, designed as parametric objects in the APM Graph environment, are included in the APM Mechanical Data, APM Construction Data, APM Technology Data databases [96-98]. They serve as a basic element for the automatic generation of drawings based on the results of calculations in engineering modules.

In the case of using parametric models, it becomes possible to store libraries of standard designs. When inserting a parametric model into a working drawing, the user sets the values of the variables used to build the parametric block. Until it into individual elements is divided, it retains all parametric links and the possibility of modifying the variables that describe the tool model.

6.4.2. Sequence of creating a parametric model

When you select the command *File/Create a model* from the main menu, APM Graph switches to the mode of creating a parametric model. A parametric model is a sequence of drawing commands with specified parameters. Parameters are set either numerically or through analytical expressions. The finished parametric model can be inserted into a regular drawing as a parametric block (see the command *Draw/Block/Insert Block*). A new item is added to the main menu: *Parameterization*.

Parameterization menu

Commands – this command calls the *Parametric Commands List* dialogue box, where you can set all the parameters of drawing commands.

Variables – the command calls the *Variables dialogue box*, in which you can add, change or delete variables.

Base point – opens the dialogue box for specifying the base point. The base point is the point that will be the insertion point for subsequent insertions of the parametric model as a block into a regular drawing.

Replace Variable – calls the dialogue box for replacing a variable. In this window, you can specify a new name for any of the existing variables, and the variable will be replaced in all expressions of the parametric model.

The sequence of creating a parametric model is usually as follows:

1. The analysis of the input data required to build the model is performed. The data is divided into initial (independent) and derived (dependent on the initial.

2. Input data in the form of variables are entered in the *Variables* dialogue box, and for the initial data only the value is set, and for the derivatives an expression that is a function of the initial and already

declared derived data. There is a single rule: a variable that is used in subsequent expressions – must be declared in advance.

3. The sequence of commands leading to the construction of the required model is graphically set.

4. Parameters for commands are indicated in the list of parametric commands, if necessary. In this case, the calculated expressions use the variables specified under No. 2, or auxiliary variables created in the process of building the model.

5. The correspondence of the model formed in this way to the required one is analyzed, and, if necessary, the command parameters are corrected or the method of constructing the entire model or its part is changed.

6. The correctness of the constructed model for various values of the initial data is analyzed.

7. The base point of the model is set. Either the base point coordinates are specified parametrically, or the coordinates of one of the existing control points are used.

After finishing work on the model, it should be saved in a separate file with the extension: .agp (using the *File/Save command*). Now the model can be inserted into a regular drawing as a parametric block (see the *Draw/Block/Insert Block* command). When inserting a parametric block, only the initial data is provided to the user for filling.

6.4.3. Parametric model of a relief tooth

Input data, in the form of variables, the *Variables* dialogue box is entered (Fig. 6.8).

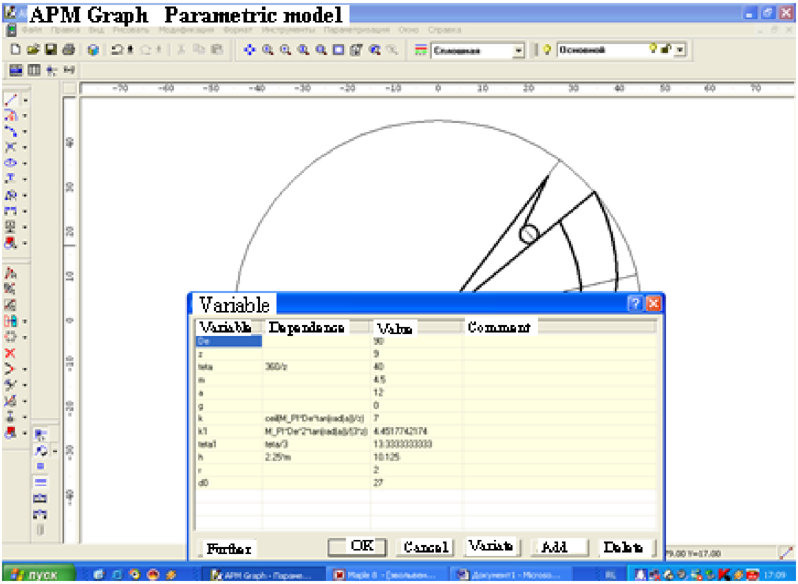


Fig. 6.8. Variables windows of APM WinMachine

These *Variables* dialogue box for IDMC-tool include:

- addendum diameter D_e;
- mounting bore diameter d_0;
- number of the milling cutter teeth z;
- module m;
- radius of curvature of the chip groove r;
- back clearance angle at the apex base point of the cutting edge α;
- tool front rake angle γ.

Moreover, only a value is set for the initial data, for example, "$D_e = 90$".

Derived data include:

- value of the first relief K;
- value of the second relief K_1;
- the circumferential pitch of teeth θ;
- angle of rotation of the radius-vector defining the space of the chip

groove θ_1.

For derived data, not only a value is set, but also an expression that is a function of the initial and already declared derived data [99-101]. Therefore, the derived value of the first relief is written in the *Variables* window in the following form (using the syntax of WinMachine analytic expressions):

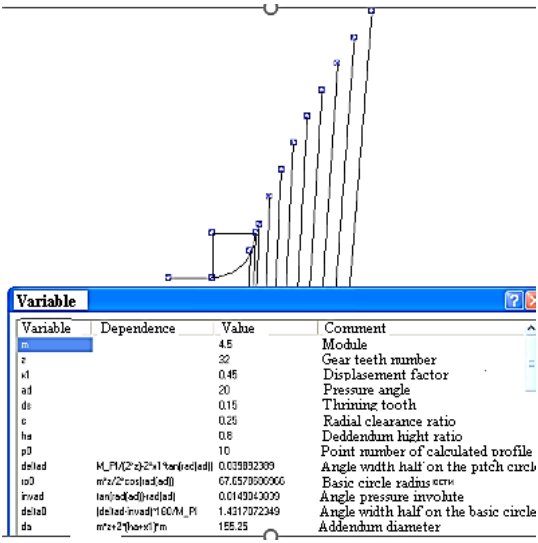
$$K = ceil(M\_Pi * D_e * \tan(rad(\alpha))/z,$$

where the *ceil* function – rounding to the smallest integer greater than the argument;

M_Pi – number "*Pi*".

6.4.4. Parametric modelling of the involute tooth contour

The input data, which as variables in the *Variables* dialogue box, include the parameters of the gear being cut are entered (Fig. 6.9).



Variable	Dependence	Value	Comment
m		4.5	Module
z		32	Gear teeth number
x1		0.45	Displasement factor
ad		20	Pressure angle
ds		0.15	Thining tooth
c		0.25	Radial clearance ratio
ha		0.8	Deddendum hight ratio
p0		10	Point number of calculated profile
deltad	M_PI/(2*z)-2*x1*tan(rad(ad))	0.039892389	Angle width half on the pitch circl
rb0	m*z/2*cos(rad(ad))	67.6570660066	Basic circle radius
invad	tan(rad(ad))-rad(ad)	0.0149043039	Angle pressure involute
delta0	(deltad-invad)*180/M_PI	1.4317072349	Angle width half on the basic circle
da	m*z+2*(ha+x1)*m	155.25	Addendum diameter

Fig. 6.9. Variables window in the task of constructing an IDMC-involute tooth profile

The algorithm for constructing an involute profile is based on a sequential step-by-step determination of the pressure angles and they are involute for a set of radii values – vectors r_x, lying in the range from the radius–vector of the dedendum circle r_i to the radius-vector of the addendum circle r_e (Fig. 6.10).

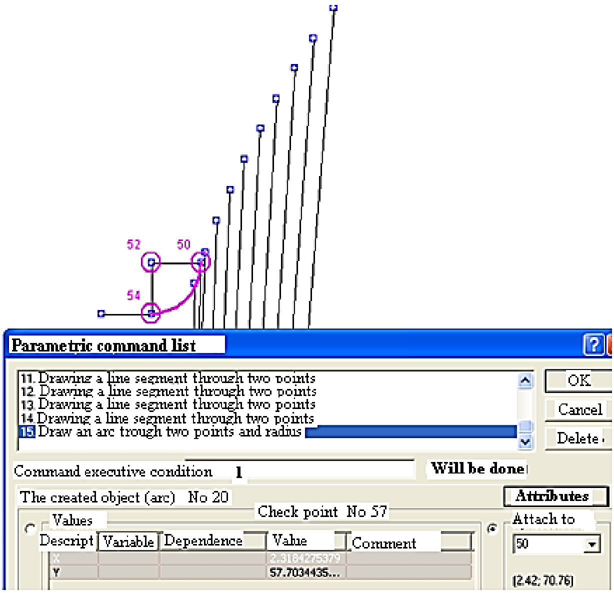


Fig. 6.10. Command window in the task of constructing an IDMC-involute tooth profile

In the upper part of the *Parametric Commands List* window, all commands used to create the model are sequentially located. Each command has its own unique set of parameters. The *Value* field is filled in automatically when creating a command. If the current command is a draw command, the object to be drawn by this command is highlighted on the screen. When you switch to a command, the screen displays the state of the drawing before its execution.

Each command has its own unique set of parameters. In the command parameters editing window, the title of the edited parameter is indicated in the header. Enter a number in the *Value* field if no expression is required for this parameter. The *Expression* field specifies an analytical or string expression for this parameter (depending on the type of the parameter). At the same time, an expression is a function of variables, predefined variables in the dialogue box, or auxiliary variables created in the process of building a model [102, 103]. In the *Comment* field, you can specify a comment for the parameter. In the *Variable* field, declare an auxiliary variable that is calculated through expression or uses, by default, the value if no expression is specified. Auxiliary variables can be used as input in parameters of subsequent commands.

In the commands for creating graphic primitives, the type of the created primitive and its index are indicated. The index of an object is an automatically assigned unique number that identifies that object. Indices are directly used in commands, the execution of which requires the indication of one or more existing objects in the drawing (drawing a line parallel to the specified one, deleting objects, etc.).

Checkpoints created with the object are also automatically indexed and can be used in subsequent commands to directly refer to already created checkpoints.

In the *Base point* window, you can specify the coordinates of the base point either parametrically, or by selecting the index of any of the existing points. The base point is the point that will be the insertion point for subsequent insertions of the parametric model as a block into a regular drawing. The parameters are the coordinates of the base point.

To set parametric coordinates of a point, select the *Values* group. Double-clicking with the left mouse button on the parameter field in the *Value* group calls the editing window for the currently selected parameter. Parameters can be set by specifying a value or an expression using input and auxiliary variables.

If you need to use the coordinates of any of the existing control points, then you should select the *Attach to point* group. In the drop-down list box, you can directly enter the index of the breakpoint. If such a point exists in the drawing, then it will be circled in the drawing, and its coordinates are displayed to the right of the list. When the list of available control points drops out (when you click the arrow to the right of the drop-down list entry field), all control points of the drawing will be highlighted. You can navigate through the points by placing the input focus on the drop-down list and pressing the cursor up and down buttons.

6.5. Basic requirements for the IDMC-working drawing

The working drawing (Fig. 6.11) must contain the necessary data on the design and all parameters that determine the shape, dimensions, tolerances, surface roughness class, material and other information necessary for the manufacture, control and operation of the disk modular cutter.

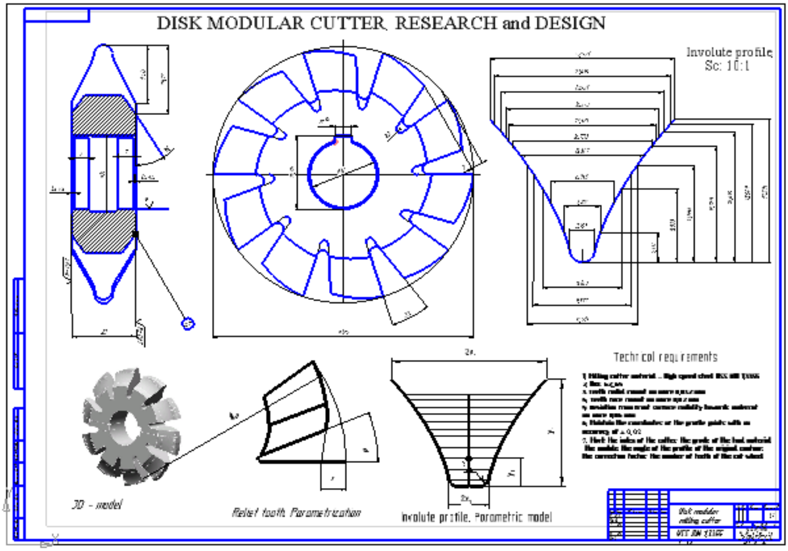


Fig. 6.11 IDMC- design project

The data required for the IDMC manufacture and control are given in the technical requirements for cutters GOST 10996-64.

In the technical requirements, it is necessary to indicate the material, the hardness of the cutting part, and the permissible deviations in the manufacture of cutters from the radially of the front surface and others.

CONCLUSIONS

1. Specialized application programs for calculation and modelling of a complex-profile gear-cutting tool based on the CAD KOMPAS-3D and APM WinMachine syntax are developed. 3D- and parametric models of the basic rack contour, the involute profile and single- and double form-relived teeth of the gear-cutting milling cutters are proposed. The developed calculation mechanism is aimed at the computational analysis of the designs research for gear-cutting tools based on the constructed solid- and parametric models are used. Moreover, each new version in parametric form is synthesized only by changing a limited set of source data, which reduces the time for multivariate design and the search for a rational structure.

2. Modification of the flanking type worm wheel hob for cutters with a modulus more than 2 mm by checking the appropriate checkbox in the KOMPAS window "Modification of a profile for shaving" are selected. Modification of the involute profile allows reducing the noise level and increasing the service life of the gear train, as well as compensating for deformations during heat treatment. When you enter the height of the flank on the gear tooth head, the flank width and the diameter of the modification circle of the gear teeth heads (passing through the starting points of the modification line) are automatically changed.

3. In the window "Calculate the flank of the cutter" change the angle of the flank. Pay attention to the value of the height and depth of modification. With an increase in the flank angle of more than 5^0 (standard 25^0), the ratio: $h_g - \Delta$ changes, while the value exceeds the limiting values.

4. The application program “CAD Mill's Cutters” (integrated into KOMPAS-3D) provides for the formation of non-standard design

parameters of worm gear cutters. Choose its rational constructive version of the hob cutter due to changes in the groove profile angle, the profile of the transition curve and size of the tongue can be implemented in multivariate form.

5. The procedure for the design of worm spline mills has been implemented in the CAD Mill's Cutters library for light, medium and heavy series of spline shafts, as well as for non-standard shapes, which expands the scope of this library.

6. The stage of a complex lateral profile approximation of a spline with a replacement circle (or arcs of two touching circles) with the calculation of the error value of such a replacement, using a criterion $h > 0.12R_W$ has been effectively implemented.

7. In the program window “Hob tooth thickness”, an express calculation of the additional profile size height is used, which allows you to control the tooth thickness on the profile scale.

8. Based on such parameters as the values of single- and double relief, taking into account the groove depth, the tooth profile in the normal section in the "Tooth geometry" window is formed. It also provides for the setting of non-standard sizes.

9. Based on the above procedures, the construction of a three-dimensional model and a drawing of a worm spline cutter are implemented.

10. The application program "Shaper gear cutter" for the design of disk-type, deep counter bore-type and shank-type tool implements the process of modelling and calculating it’s both standard structures and non-standard structures. The “Calculated parameters” window displays a set of options for non-standard cutters at several of the base sector shifts. Displacement basic section, which is the basis for modelling and choosing the best option. The program provides access to the Database of standard designs.

11. The Shaper gear cutter program offers a "friendly" interface with note fields, where the results of a check calculation for the suitability of a given shaper cutter for processing a gear wheel are displayed.

12. As a result of the design process, the construction of a three-dimensional model and a drawing of a shaper cutter was realized.

13. The method of calculation of Interlocking Disk Milling Cutter (IDMC) working by the form-copying method is presented. Two main types of gear groove profile are considered: type I, in which its contour of the root bottom is outlined by the “straight-circular arc” profile and type II – with a contour in the form of a circular arc. At the same time, an analytical method was used to construct the lateral involute profile of the tooth, as well as the one- and two-relief of the IDMS-back surface.

14. Graphic primitives of contours for complex-profile gear cutting tools have been developed. Significantly increases the productivity of the designer, giving him an alternative to standard graphic primitives (line segment, an arc of a circle, etc.) is a consequence of the proposed graphic primitives using. This is one of the most effective ways to improve the technical level of design decisions.

15. The proposed approach provides for the verification of permissible variants of the cutter tooth contours by entering restrictions into the parameterization program in the form of a message variable. These variables reflect the position of the non-working part of the tooth profile, with a positive distance of the transition curve from the elongated epicycloid.

16. The use of the CAD KOMPAS-3D and APM WinMachine parameterization toolkit makes the process of designing the gamma of a modern complex profile cutting tool a very effective procedure using finite element analysis and solid modelling. In the environment of the KOMPAS-3D and APM Studio module, a three-dimensional model of a gear-cutting hob cutter was constructed and the stress-strain state of the working surface of the tooth was analyzed.

Appendix 1

CALCULATION RESULTS OF THE WORMWHEEL HOB PROFILE:

(Gear wheel with modification)

Designation .... WH -00000

Initial data (gear parameters)

Module... .... 5 mm.

Profile angle .... 20^0.

The diameter of the teeth tops …….. 175 mm.

Pitch diameter .... 165 mm.

The gear dedendum diameter of the cogwheel cavities .... 152.5 mm.

Wheel tooth thickness .... 7.85 mm.

Tooth line direction .... Left

Initial data of the cutter

Milling cutter embodiment (length) .... Normal length

Number of thread 1

Design type .... Type 1

Technological type .... finishing

Accuracy class.. AAA

Profile modification .... with modification

Allowance.. 0.095 mm.

Radial clearance coefficient .... 0.25 mm.

Profile modification (data)

Modification type .... Flanks

Number of wheel teeth, z_1 0

New profile angle .... 20^0.

The module on the engagement circle ……...................................... 5 mm.

The angle of teeth line inclination on engagement circle …................... 0^0.

The diameter of the engagement circle .... 165 mm.
The normal thickness of the tooth on the engagement circle ..… 7.85 mm.
The angle of inclination of the wheel teeth ……................................... 0^0.

Profile parameters in the normal section

Teeth angle ....……………………….. 20^0.
Tooth thickness .... 7.762963 mm.
Tooth apex height .... 6.25 mm.
Tooth bottom land height .... 6.25 mm.
Tooth height .... 12.5 mm.
The radius of the apex rounding .... 1 mm.
The radius of the bottom land rounding .... 1.5 mm.

Profile modification (tongue)

Tongue conjugated angle ....0^0.
Tongue type ....…………………………….-
The height of the beginning of the tongue ....…………… 0 mm
Tongue length ....0 mm.
Tongue width .... 0 mm.

Profile modification (flanks)

Flank height on the wheel tooth .... 0.6 mm
Distance from the flank beginning to basic line ……….. 10.138067 mm.
Flank angle .... 25^0.
Flank size .... 10.788706 mm.
The flank thickness at the gear top ……………….................0.051259 mm.

Dimensions

Front rake angle (angle gamma) .... 0^0.
Back clearance angle at the top of the teeth .... 10^0.
The back clearance angle on the lateral sides .... 3.451178^0.
The number of chip grooves .... 14 mm.
Groove angle .... 25^0.
Rounding the groove .... 2 mm.

Relief value ….. 6.5 mm.
The size of the double relief .... 9.8 mm.
Groove depth ....……… 21.700001 mm.
The length of the grinding part of the teeth .... 10.471975 mm.
The thickness of the tooth in the cavity of the groove .... 8.385607 mm.
Average cutter diameter .... 125.550003 mm.
Groove diameter ....…………………… 52 mm.
Bead diameter .... 94 mm.
Cutter length .... 140 mm.
Cutter addendum diameter .... 140 mm.
Bead length .... 5 mm.
Mounting bore length .... 40 mm.
Thread helix line angle .... 2^0 17'
The step of the cutter along the axis .... 15.720445 mm
Pitch projection on axis .... 15.695492 mm.

Mounting bore parameters

Mounting bore diameter .... 50H4 mm.
Height to keyway .... 53.5H12 mm.
Keyway width .... 12C11 mm.
The radius of the keyway rounding .... 1.1 mm.
Symmetry tolerance of the keyway in radius expression …………………………………………………....0.09 mm.

Control parameters

Radial runout tolerance of beads .... 0.004 mm.
Face runout tolerance of beads .... 0.003 mm.
Tolerance of full radial runout of the teeth tops …….............. 0.012 mm.
Tolerance of the profile deviation of the front surface............... 0.012 mm.
Admissible deviation of the difference between adjacent circumferential pitches .... 0.016 mm.
Admissible deviation accumulated error of the circumferential pitch of chip grooves ………………………………………………..0.025 mm.

Admissible deviation direction of chip grooves (+/-) .... 0.04 mm.
Tolerance of tooth profile deviation .... 0.005 mm.
Tolerance of tooth thickness deviation .... -0.025 mm.
Admissible deviation axial pitch of the cutter (+/-) .... 0 mm.
Admissible cumulative pitch deviation over the length of
any three pitches ………………………………………………..…. 0 mm.
Admissible deviation of the cutter helix from
tooth to tooth .... 0.004 mm.
Admissible deviation of cutter helix on one revolution …….. 0.007 mm.
Admissible deviation of cutter helix at three revolutions .... 0.01 mm.
Admissible deviation of engagement error from tooth to tooth. 0.004 mm.
Tolerance deviation of the engagement error ....…………..0.008 mm.
Roughness of the mounting bore, R_a .... 0.4 μm
Roughness of the front surface, R_z .... 1.6 μm
Roughness of the back lateral surface, R_z .... 1.6 μm
Roughness of the back surface along the teeth apexes, R_z ………. 1.6 μm.
Roughness of a bead cylindrical surface, R_z .... 1.6 μm.
Roughness of the bead end, R_a .... 0.4 μm.
The projection of the tooth thickness on the axial plane ……. 7.7568 mm.
The projection of the profile angle onto the axial plane .... 19.985378^0.
Projection of the pitch of the helical groove .... 9892.131836 mm.

Appendix 2

RESULTS OF CALCULATING THE PROFILE OF THE WORM SPLINE CUTTER (WSC)
(Straight-sided spline shaft)

Designation....................... .... WSC-00000

Initial data (parameters of the spline shaft)

External diameter .... 40 (-0.31; -0.47) mm.
Chamfer .... 0.4 (0.2; 0) mm.
Minimal value "*a*" .... 3.46 mm.
Internal diameter .... 36 (-0.05; -0.089) mm.
Thickness spline .... 7 (-0.013; -0.035) mm.
Minimum height of a straight section... 1.19 mm.
Centering method.. 1
Number of
splines...8
Root rounding radius... 0 mm.
Basic circle diameter ....38.772694 mm.

Calculation results

Minimum height of the straight section (cutter) .... 2.139998 mm.
Front rank angle γ .... 0.180906^0
Calculated addendum diameter .... 38.889999 mm.
Calculated dedendum diameter .... 35.9305 mm.
Calculated width of the spline .... 6.976 mm.
Profile height from basic line .... 1.912274 mm.

Minor arc

X-coordinate .... 8.216448 mm.
Y-coordinate .... 1.735666 mm.

Arc radius R .... 8.397771 mm.

Major arc

X-coordinate .... 0 mm.
Y-coordinate .... 0 mm.
Arc radius R .... 0 mm.

Design parameters of cutter teeth

Tongue height .... 0.491176 mm.
Tongue thickness... 0.421447 mm.
Tongue profile angle... 45^0.
Spline milling cutter pitch in normal section.................... 15.226002 mm.
Teeth thickness at the basic line .... 8.211805 mm.
Width of the groove.. 0.058653 mm.
Groove depth .... 0.560166 mm.
Full height of the teeth .... 4.531092 mm.
Keyseat diameter .... 0 mm.
Flank angle .... 35^0.
Spline milling cutter accuracy rating .... A.
Spline series .... Light series
Tooth thickness on the tip .... 6.907041 mm.
First height from basic line .... 1.421098 mm
Tooth thickness at first height... 7.342636 mm.
First height from tip .... 0.491176 mm.
Second height from basic line .... 0.64 mm.
Tooth thickness at second height ....7.888381 mm.
Second height from tip .... 1.272274 mm.
Third height from basic line .... 0 mm.
Tooth thickness at third height .... 0 mm.
Third height from tip .... 0 mm.
Flank height from basic line .... -0.058653 mm.

Tooth thickness at flank .... 8.236149 mm.
Flank height from tip .... 1.970926 mm.

Construction size

Front rank angle γ (gamma corner) .... 0°.
Back clearance angle on the tip of the teeth (α_{tp})................................ 12^0.
Back clearance angle on lateral sides α_l)....................................2.515476^0
Chips groove number…... 12.
Groove angle .... 25^0.
Groove rounding .... 2 mm.
Value of relieving .... 6.5 mm.
Value of the double relieving .... 8 mm.
Groove depth.. 13.138 mm.
Length of the grinding part of teeth .... 6.981317 mm.
Tooth thickness in groove root ....10.94007 mm.
Mean diameter of spline milling cutter .... 74.225456 mm.
Groove diameter .... 29 mm.
Bead diameter .... 50 mm.
Spline milling cutter length .... 70 mm.
Spline milling cutter addendum diameter .... 80 mm.
Bead length .... 5 mm.
Mounting bore length .... 20 mm.
Thread helix angle ……………………... 3^0 45’
Spline milling cutter pitch on-axis .... 15.258672 mm.
Pitch projection on axis .... 15.193401 mm.

Mounting bore parameters

Mounting bore diameter .... 27H5 mm.
Height to keyway .... 29.8H12 mm.
Width of the keyway .... 7C11 mm.
Radius of keyway rounding .... 0.9 mm.
Symmetry tolerance of the keyway in radius terms …………..… 0.09 mm.

Controlling parameters

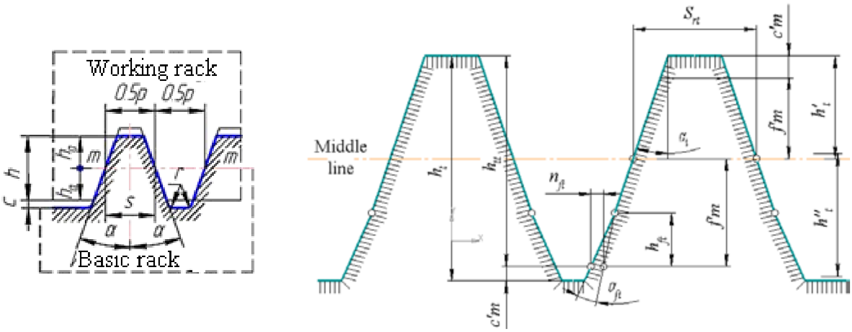
Radial run-out tolerance of the bead .... 0.006 mm.
Face run-out tolerance of the bead.. 0.005 mm.
Full radial run-out tolerance of the teeth tips .... 0.032 mm.

Straightness tolerance of front rake surfaces on
operation height ………………………………………………… 0.032 mm.
Permissible deviation of neighboring circular pitch
differences .... 0.032 mm.
Permissible deviation of accumulated circular pitch error
of chip grooves ……………………………………………….. 0.063 mm.
Permissible deviation of chip grooves direction (+/-).................. 0.08 mm.
Permissible deviation of tooth profile ....Not more than 2/3 times of tolerance zone value on spline shaft teeth thickness on the height 0.2 mm from tooth tip (deviation only in plus) and not more1/3 times of tolerance zone value on spline shaft teeth thickness on the mean full tooth height (deviation only in plus)
Permissible deviation of tooth thickness...................................... Not more than 1/3 times of tolerance zone value on spline shaft teeth thickness
Permissible deviation of spline milling cutter at one turn .... 0.016 mm.
Permissible deviation of axial tooth pitch (+/-) .... 0.01 mm.
Permissible deviation of axial pitch between teeth..................... 0.02 mm.
Mounting bore roughness, Ra .... 0.32 µm
Roughness of the front rake surface, Ra .... 0.63 µm
Roughness of the back lateral surface, Ra .... 0.32 µm
Roughness of the back surface at the tip of the teeth, Ra .... 0.32 µm
Roughness of the bead cylinder surface, Ra .... 0.32 µm
Roughness of the bead end, Ra .... 0.63 µm
Groove helix pitch .... 3557.73291 mm.

Appendix 3

PRESSURE ANGLE AND ENGAGEMENT ANGLE

The main parameters of the teeth of the spur wheels are determined by the dimensions of the basic contour of the gear rack (GOST 13755-81), and the dimensions of the teeth of the gear cutting tool are determined by the parameters of the basic contour of the tool rack (Fig. A1 a, b) [1, 4]



a b

Fig. A1. The original contours of the gear wheel (a) and the tool (b)

To ensure uniformity of manufacture and interchangeability of gear wheels, the engagement parameters are standardized. The shape and dimensions of the wheel teeth and the gear-cutting tool are determined by the *original contour* (the projection of the profile of the cutting tool onto a plane perpendicular to the axis of the workpiece). For modules over 1.0 mm, the original contour (GOST 13755-81) is characterized by the following parameters (Fig. A1): profile angle: $\alpha = 20$; depth of entry: $h = 2h_a^* m$, where $h_a^* = 1.0$ – coefficient of the height of the tooth head; the thickness of the tooth along the pitch line: $s = 0.5p$; radial clearance: $c = c^* m$ ($c^* = 0,25$ – radial clearance coefficient); radius of curvature at the root of the tooth: $r = 0.38\ m$.

The tool rack differs from the toothed rack as follows:

1. The head height h_t' should be larger by the size of the radial clearance in the gear.

2. Tooth thickness S_0 should be larger by the size of the radial clearance in the gear.

3. Flank location: On the tool rack, it is located on the tooth root, and on the toothed rack on the tooth head

The engagement of the involute gearwheel with the rack is the basis for cutting gearwheels by the form-generating method. For the straight cutting edge of the tool bar tooth to form an involute profile, it is necessary to change its position relative to the cut tooth. This movement is called the *form-generating movement*. The envelope of the row in the position of the cutting edge of the rack tooth forms the involute tooth profile of the cut wheel.

The *engagement angle* and the *involute pressure angle* are two different concepts. According to GOST 16531-83, the angle of engagement α_{tw} (α_w) is understood as an acute angle in the main section of the involute gear transmission between the line of engagement A_1A_2 and the perpendicular to the line of centres O_1O_2 (Fig. A2). The engagement of the shaper with the gear wheel during the cutting process is called machine engagement. The angle of the machine engagement of the new shaper with the wheel α_{10} is determined by (1).

Thus, this term can only be used if a pair of conjugating profiles are being considered. If an element of engagement: a wheel or a tool – is taken separately, then, naturally, there are no lines of engagement and a line of centres for it. In addition, during the cutting process, the tool engages with a wide variety of engagement angles, which differ significantly from, for example, 20^0.

The *pressure angle* α_p (α) is understood as the angle between the tangent to the involute (*KK*) at any point of the involute and the radius vector OA_1 drawn to the same point of the involute (Fig. A3).

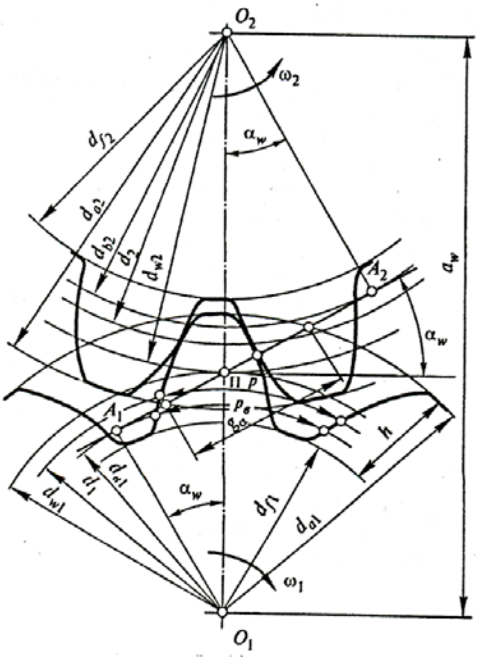


Fig. A2. Geometric parameters of the engagement

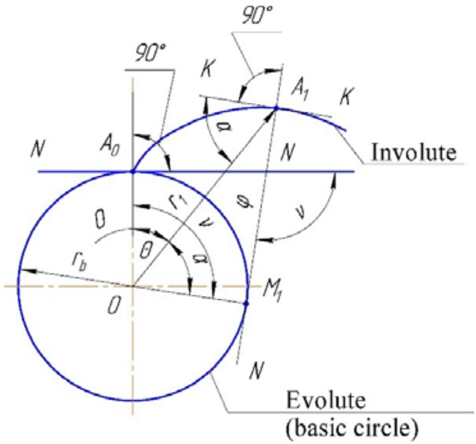


Fig. A3. Involute formation

From the way the involute is formed, it follows:
- the involute cannot exist inside the base circle and has two branches depending on the rotation direction of the generating line N-N;
- two evolvents of the same name are equidistant curves, i.e. the distance between them, measured along any common normal, is the same and equal to the straightened arc of the base circle between the involutes origins;
- the normal drawn at any point of the involute is tangent to the base circle;
- the involute radius of curvature at any point is equal to the length of the tangent from this point to the base circle.

Thus, the *pressure angle* α refers to the involute as to a geometric line. It can vary widely (from 0 to ∞).

To avoid inaccuracies in the wording, it is recommended that instead of the "engagement angle" or "pressure angle" indicate the "*profile angle*" α_0 (α_i) shown in Fig. A4. Determination of the profile angle of the cutter in clause 3 of this monograph is given.

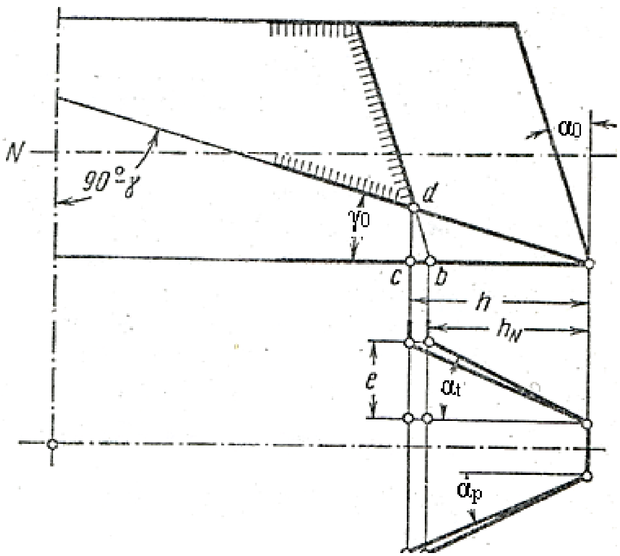


Fig. A4. Shaper profile angle

Appendix 4

TOOL DISPLACEMENT WHEN CUTTING THE TEETH AND ITS INFLUENCE ON THE SHAPE AND STRENGTH OF THE TEETH

Correlation adjustment of gears (from Latin corrigo – I correct, improve), a technique for improving the teeth shape of the involute gearing. When cutting gears, the original standard contour of the producing rack is a shift in the radial direction so that its pitch line does not touch the pitch circle of the wheel. In this case, you can use a normal rack and pinion gear cutting tool: a comb, a hob cutter or shapers.

Processing on a gear-cutting machine by the form-generating method is carried out, cutting wheels with the required shift of the original contour. *Correlation adjustment of gears* appeared as a means of eliminating unwanted root undercutting on wheels with a small number of teeth due to tool imperfections. Modern correction of gears has a more general meaning and is practically expressed in the deliberate shift of the original contour, which is one of the main geometric parameters of gears (Fig. A5, 1; 2)

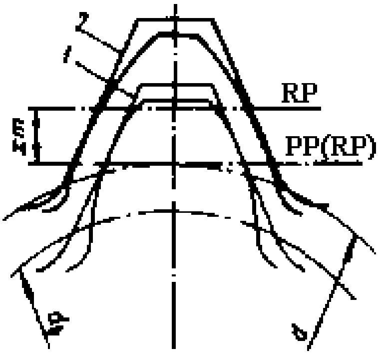


Fig. A5. Tool shift (racks)

Fig. A5 shows two positions of the tool (rack) when cutting teeth: 1 – the pitch plane of the rack (PP) coincides with the basic plane (BP) – cutting without displacement; 2 – the tool is given a positive shift $x{\cdot}m$. The displacement from the center is considered positive ($x > 0$), and towards the center – negative $x < 0$). In this case, the base d_b and pitch d diameters of the wheel do not change, since z does not change (the *LP* still rolls along with diameter d, and the *PP* is a shift by $x\ m$).

As can be seen from Fig. A5, tool displacement caused a significant change in the tooth shape. The thickness of the tooth at the root has increased, and the strength of the tooth in terms of bending stresses has also increased. At the same time, the head of the tooth sharpened. Sharpening is one of the reasons for limiting the value of tool shift. The negative tool displacement is accompanied by phenomena of the opposite nature.

There are two types of shift gears:

1. The gear is made with a positive shift ($x_1 > 0$), the wheel – with a negative ($x_2 < 0$), but so that $|x_1| = |x_2|$ or $x_\Sigma = x_1 + x_2 = 0$. This method is called "high-altitude correction".

For any displacement, the sum of the width of the bottom land and the thickness of the tooth along the pitch circle is equal to the pitch p. Displacements of the same magnitude but different in sign, cause the same increase in the thickness of the gear tooth and the width of the wheel root. Therefore, in the engagement of the gear pair at $x_\Sigma = 0$, the pitch circles touch and are initial, as in the transmission without displacement. The centre distance a_w and the engagement angle α_w also do not change:

$$a_w = a = 0{,}5(d_1 + d_2); \qquad \alpha_w = \alpha = 20^\circ.$$

Only the ratio of the heights of the heads and root of the teeth changes.

High-altitude correction is used to eliminate undercutting of the tooth root and increase the strength of the gear teeth.

2. The total displacement x_Σ is not equal to zero. Usually $x_\Sigma > 0$, as well as $x_1 > 0$ and $x_2 > 0$. This method is called "angular correction". With positive x_1 and x_2, the pitch thickness of the gear and wheel teeth is greater than $p/2$. Therefore, the pitch circles cannot touch. New circles that are larger than the dividing ones become initial ($d_{w1} > d_1$; $d_{w2} > d_2$, see Fig. A2). The center distance increases:

$$a_w = 0.5\,(d_{wl} + d_{w2}) > a = 0.5(d_l + d_2).$$

In this case, the angle of inclination of the engagement line also increases as a common tangent to the base circles, i.e., the angle of engagement increases: $\alpha_w > \alpha = 20^0$. An increase in a_w is accompanied by a decrease in the overlap coefficient ε_α, which is negative and is one of the reasons limiting the use of large displacements. The coefficient of (end face) overlaps ε_α is understood as the ratio of the active line length of engagement g_α to the base circumferential pitch of the teeth p_b (Fig. A2).

Angular correction is used if it is necessary to design a gear pair with a given centre distance and at the same time increase the strength of the gear and wheel teeth.

Shift cutting allows in many cases to improve the quality of the gearing. When applying shift, you need to remember:

1. Positive displacement increases the bending strength of the teeth and eliminates undercutting at a small number of teeth (lowers $z_{\min}$). For example, at $z = 25$, increasing x from zero to +0.8 – reduces the tooth shape factor Y_{FS} by 1.2 times. Correspondingly, the bending stress σ_F decreases. by the tabular data, you can reduce $z_{\min}$ from 17 to 8.

2. An increase in α_w at $x_\Sigma > 0$ – increases the contact strength. It is possible to increase α_w up to 25^0 and increase the permissible load by about 20%.

3. With a large number of teeth at the gear and wheel, the shift is ineffective, since the shape of the tooth, even with significant shifts, hardly changes. (For a rack, which is like a wheel at $z = \infty$, the shift does not change the shape of the tooth at all.)

Gears with the shift at $x_\Sigma = 0$ are used for large gear ratios and small z_1. Under these conditions, the displacements $x_1 > 0$ and $x_2 < 0$ equalize the shape of the gear and wheel teeth and bring them closer to equal bending strength. Recommendations for the selection of shift coefficients are given in GOST 16532-70.

Correlation adjustment of gears allows you to change the centre distance in gears, which makes it possible to solve several important design problems. For example, in gearboxes, planetary gears, etc., it can be placed between two transmission shafts, in which the same wheel engages with wheels having different numbers of teeth, or non-standard gears can be replaced with standard ones during repairs.

REFERENCES

1. Semenchenko I.I., Matyushin V.M., Sakharov G.N. Design of metal-cutting tools. – M.: Mashgiz, 1963. – 953 p.

2. Guidelines for the course design of metal-cutting tools: Textbook. Manual for Universities / Under total ed. G.N. Kirsanov. – M.: Mashinostroenie, 1986. – 288 p.

3. Ivan R. Law. Gear and Gear Cutting. – Hemel Hempstead: Special Interest Model Books, 1998. – 136 p.

4. Handbook of the toolmaker / I.A. Ordinartsev, G.V. Filippov, A.N. Shevchenko and others; Under total. ed. I.A. Ordinartseva. – L.: Mechanical engineering. Leningr. department, 1987. – 846 p.

5. Gear Cutting Tools. Precision Cutting Tools and Machines. – Wilhelm FETE GMBH, 2006. – 200 p.

6. Fritz Klocke. Zahnrad- und Getriebetechnik: Auslegung-Herstellung-Untersuchung-Simulation. – München: Carl Hanser Verlag CmbH & Co. KG, 2016. – 660 p. (in German)

7. Ganin, N.B. Trekhmernoe modelirovanie v KOMPAS-3D [Three dimension modeling in KOMPAS-3D]. – Moscow: DMK, 2012. – 776 p.

8. Ganin, N.B. (). Proektirovanie i prochnostnoy raschet v sisteme KOMPAS-3D [Design and strain calculation in KOMPAS-3D system]. – Moscow: DMK, 2011. – 320 p.

9. Krol O., Sokolov V.: Development of models and research into tooling for machining centers. Eastern-European Journal of Enterprise Technologies, 2018, Vol. 3, Issue 1 (93), 12–22. https://doi.org/10.15587/1729-4061.2018.131778

10. Krol, O., Sokolov, V.: Modelling of spindle nodes for machining centers. Journal of Physics: Conference Series, 1084, 012007 (2018). https://doi.org/10.1088/1742-6596/1084/1/012007

11. Shevchenko S., Mukhovaty A., Krol O. Gear Clutch with Modified Tooth Profiles. Procedia Engineering, 206, 979–984 (2017). https://doi.org/10.1016/j.proeng.2017.10.581

12. Magomedov, A., Alehin, A. (2010). Integrirovannyiy konechno-elementnyiy analiz v KOMPAS-3D [Integrated finite element analysis in KOMPAS-3D]. CAD/CAM/CAE observer, 8(60), 1–5.

13. Platonov, L. (2013). Machinostroitelnoe proektirovanie v KOMPAS-3D V.14 na novom vitke razvitiya ili poleznyie novinki paketa obnovleniy MCAD SP1 ot ACKON. SAPR i grafika. – [CAD and graphics], 10, 6–12.

14. Golovanov, V. (2013). KOMPAS-3D ot “Shaft” k “Valam i mekhanicheskim peredacham” [From “Shaft” to “Shafts and mechanical transmission”]. SAPR i grafika. – [CAD and graphics], 5, 22–23.

15. Platonov, L. (2014). 15 novinok KOMPAS-3D V.15 [15 novelties of KOMPAS-3D V.15]. SAPR i grafika. – [CAD and graphics], 6, 7–21.

16. Handbook of the toolmaker-designer / V.I. Klimov, A.S. Lerner, M.D. Pekarsky and others. – M.: Mashizdat, 1958. – 608 p.

17. Eric Oberg. Spiral and Worm Gearing. – London: Old Hand Book, 2018. – 282 p.

18. Freifeld I.A. Calculations and designs of special metal-cutting tools. – M: GNTI engineering literature, 1969. – 196 p.

19. Yulikov M.I. Design and production of cutting tools / M.I. Yulikov, B.I. Gorbunov, N.V. Kolesov. – M.: Mashinostroenie, 1987. – 296 p.

20. Shchegolkov N.N. Cutting tools. Laboratory workshop / N.N. Shchegolkov, G.N. Sakharov, O.B. Arbuzov et al. – M.: Mashinostroenie, 1984. – 168 p.

21. Weck M, Brecher C (2008) Werkzeugmaschinen 1 - Maschinenarten und Anwendungsbereiche [Machine tools 1 – types of machine tools and range of application], 6th edn. Springer, Berlin (in German).

22. Krol, O.S., Burlakov, E.I. (2013). Modelirovanie shpindelnogo uzla obrabativayushego zentra [Modeling of spindle node for machining center]. Visnik NTU “HPI”.–. [Bulletin of the NTU “HPI”], 11(985), 33–38.

23. Krol, O.S., Krol, A.A., Burlakov, E.I. (2013). Tverdotelnoe modelirovanie i issledovanie shpindelnogo uzla obrabatyivayuschego tsentra. [Modeling of spindle node for machining center]. Visnik NTU “HPI”.–. [Bulletin of the NTU “HPI”], 16(989), 14–18.

24. Handbook of a technologist of a mechanical engineer. In 2 volumes / Ed. A.G. Kosilova and R.K. Meshcheryakova – 4th. ed. revised and add. – M.: Mechanical engineering, 1986 – 496 p.

25. Rodin P.R. Metal-cutting tools: Textbook for Universities. – K.: High school, 1986. – 455 p.

26. Krol O., Sokolov V.: Parametric Modeling of Gear Cutting Tools. In: Advances in Manufacturing II. Lecture Notes in Mechanical Engineering, vol. 4, 3-11. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-16943-5_1

27. Krol O., Sokolov V.: Parametric Modeling of Transverse Layout for Machine Tool Gearboxes. In: Advances in Manufacturing II. Lecture Notes in Mechanical Engineering, vol. 4, 122-130. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-16943-5_11

28. Bolotovskiy, I.A., Ed. (1986). Spravochnik po geometricheskomu raschetu evolventnyih zubchatyih i chervyachnyih peredach [Handbook on the geometric calculation of involute gear and worm gears]. – Moscow: Mashinostroenie. – 448 p.

29. Maslov, A.R. (2006). Instrumentalnyie sistemyi mashinostroitelnyih proizvodstv [Instrumental systems of machine-building productions]. Moscow: Mashinostroenie. – 336 p.

30. Krol, O., Sokolov, V.: 3D modelling of angular spindle’s head for machining centre. Journal of Physics: Conference Series 1278, 012002 (2019). https://doi.org/10.1088/1742-6596/1278/1/012002

31. Krol, O., Porkuian, O., Sokolov, V., Tsankov, P.: Vibration stability of spindle nodes in the zone of tool equipment optimal parameters. Comptes rendus de l'Acade'mie bulgare des Sciences 72(11), 1546-1556 (2019). https:// doi.org/10.7546/CRABS.2019.11.12

32. Krol, O., Sokolov, V., Tsankov, P.: Modeling of vertical spindle head for machining center. Journal of Physics: Conference Series 1553 012012 (2020). https://doi.org/10.1088/1742-6596/1553/1/012012

33. Yashcheritsyn P.I. Fundamentals of metal cutting and cutting tool / P.I. Yashcheritsyn, M.L. Eremenko, N.I. Zhigalko. – Minsk: Higher school, 1975. – 528 p.

34. Moiseenko O.I., Pavlov P.E., Didenko S.I. Carbide gear cutting tools. – M.: Mashinostroenie, 1977. – 190 p.

35. Krol, O., Sokolov, V.: Research of modified gear drive for multioperational machine with increased load capacity. Diagnostyka 21(3), 87-93 (2020). https://doi.org/10.29354/diag/126026

36. Calculation and design of metal-cutting tools using a computer / S.I. Lashnev, M.I. Yulikov. – M.: Mashinostroenie, 1975. – 394 p.

37. Methodical instructions for the implementation of sections of coursework and thesis: Calculation and design of hob cutters for cutting spline shafts with a straight-sided profile / Comp. L.S. Kravchenko. – Kharkov: KhPI, 1987. – 30 p.

38. Krol, O., Sokolov, V.: Selection of worm gearing optimal structure for machine rotary table. Diagnostyka 22(1), 3-10 (2021). https://doi.org/10.29354/diag/129949

39. Krol, O., Sokolov, V.: Optimization of Processing Modes on Multioperational Machines Using Two-parameter D-Partitions. 2020 International Russian Automation Conference (RusAutoCon), pp. 57-62. IEEE (2020). https://doi.org/10.1109/RusAutoCon49822.2020.9208120

40. Krol, O., Sokolov, V.: Research of toothed belt transmission with arched teeth. Diagnostyka 21(4), 15-22 (2020). https://doi.org/10.29354/diag/127193

41. Feldshtein E.E., Kornievich M.A. Metal cutting tool. Constructor reference. – Minsk: New knowledge, 2009. – 1039 p.

42. Metalworking carbide tools: Handbook / V.S. Samoilov, E.F. Eichmans, V.A. Falkovsky and others. – M.: Mashinostroenie, 1988. – 386 p.

43. Sakharov G.N. Form-generating tools. – M.: Mashinostroenie, 1983. – 232 p.

44. Zovulyan G.G., Adam Ya.I. Gear cutter reference book. – M.: Mashinostroenie, 1983. – 223 p.

45. Krol O., Shumakova T., Sokolov V. Design metal cutting instruments by dint of system of KOMPAS. – Lugansk: V. Dahl EUNU, 2013. – 144 p.

46. Guidelines for the course design of metal-cutting tools: Textbook. Manual for universities / Under total. ed. G.N. Kirsanov. – M.: Mechanical engineering, 1986. – 288 p.

47. Feldstein E.E., Kornievich M.A. Cutting tool. Exploitation. – Minsk: New knowledge, 2012. – 256 p.

48. Feldstein E.E. Cutting tool. Course and diploma design. – Minsk: Design PRO, 2002. – 221 p.

49. Reference designer-toolmaker / Under total. ed. V.I. Baranchikov. – M.: Mashinostroenie, 1994. – 560 p.

50. Krol, O.S. and Osipov, V.I. (2013). Modeling of construction spindle's node machining centre SVM1F4. TEKA Comission of Motorization and Power Industry of Agriculture, 13, 3, 108 – 113.

51. Krol, O., Sokolov, V.: Modeling Carrier System Dynamics for Metal-Cutting Machines. 2018 International Russian Automation Conference (RusAutoCon). IEEE (2018).
https://doi.org/ 10.1109/RUSAUTOCON.2018.8501799.

52. Krol O., Shevchenko S., Sukhorutchenko I. and Lysenko A. (2014). 3D-modeling of the rotary table for tool SVM1F4 with non-clearance worm gearing. TEKA Commission of Motorization and Energetic in Agriculture, 14, 1, 126-133.

53. Ryzhkin A.A., Shuchev K.G., Skhirtladze A.G. Cutting tool. – M.: Phoenix, 2009. – 403 p.

54. Krol O., Sokolov V.: Modeling of Spindle Node Dynamics Using the Spectral Analysis Method. In: Advances in Design, Simulation and Manufacturing III. DSMIE 2020. Lecture Notes in Mechanical Engineering, vol. 1, pp. 35-44. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-50794-7_4

55. Kozhevnikov D.V., Grechishnikov V.L., Kirsanov S.V. Cutting tool. – M.: Mashinostroenie, 2005. – 528 p.

56. GOST 2249-93 Processing of cutting. Termini, viznachennya. – K.: Derzhstandart Ukrainy, 1994. – 53 p.

57. Krol, O., Sokolov, V., Tsankov, P., Logunov, O.: Modelling of machining center vibration stability by the D-partitions method. Journal of Physics: Conference Series 1745 012085 (2021). https://doi.org/10.1088/1742-6596/1745/1/012085.

58. Krol, O., Tsankov, P., Sokolov, V. (2018). Rational choice of two-support spindles for machining centers with lubrication system. *EUREKA: Physics and Engineering*, 3, 52–58. https://doi.org/10.21303/2461-4262.2018.00648

59. Krol, O.S. (2014). Metodyi i protseduryi dinamiki shpindelnyih uzlov: monografiya [Methods and procedures for the dynamics of spindle nodes: monograph]. Lugansk: VNU. – 154 p.

60. Krol, O., Zhuravlev, V (2013) Modeling of spindle for turret of the specialized tool type SF16MF3. TEKA Commission of Motorization and Power Industry of Agriculture, 13, 4, 141–147.

61. Feldshtein E.E., Kornievich M.A. Cutting tool. Tutorial. – Minsk: New knowledge, 2007. – 400 p.

62. Krol, O., Sukhorutchenko, I. (2013). 3D-modeling and optimization spindle's node machining centre SVM1F4. TEKA Comission of Motorization and Power Industry of Agriculture, 13, 3, 114–126.

63. Krol O.S. Methods and procedures for optimizing cutting conditions. Monograph. [Metodyi i protseduryi optimizatsii rezhimov rezaniya. Monografiya]. – Lugansk: Publishing house VDEUNU, 2013. – 260 p.

64. Krol O.S. Methods and procedures for the dynamics of spindle nodes. Monograph. – Lugansk: EUNU, 2014. – 154 p.

65. Krol, O.S. Parametricheskoe modelirovanie metallorezhuschih stankov i instrumentov. [Parametric modeling metalcutting tool and instruments]. Lugansk: SNU, 2012. – 116 p.

66. Methodical instructions for course and diploma design "Designing gear cutters using the KOMPAS system" / Comp. O.S. Krol, V.A. Plakhotnik, A.V. Mitsyk. – Lugansk: Publishing house of VNU im. Dahl, 2011. – 52 p.

67. Krol O., Sokolov V. Rational choice of machining tools using prediction procedures/EUREKA: Physics and engineering, is. 4, 2018. – P. 14–20.

68. Krol O.S., Krol A.A., 2011: Calculation of compliance SF68VF4 machine dynamics shaping and modeling // Vestnik SevNTU. Ser. Engineering and Transportation. – is. 117, 81–84.

69. Krol, O.S., Suhorutchenko, I.A. (2014). Trehmernoe modelirovanie obrabatyivayuschiy tsentra SVM1F4 v KOMPAS 3D [Solid modeling of machining centre SVM1F4 in KOMPAS 3D]. Eastern-European Journal of Enterprise Technologies], 4/7(70), 13–18.

70. Design of metal-cutting machine tools and machine-tool systems: Handbook-textbook. In 3 volumes. Vol. 2. Part 1. Calculation and design of units and elements of machine tools / A. S. Pronikov, E. I. Borisov, V. V. Bushuev et al. – Moscow: Mechanical Engineering, 1995. – 371 p.

71. Balmont V.B. Gorelik I. G., Figatner A. M. Calculations of high-speed spindle nodes / NIITEMR, Ser. 1, 1987, No. 1. – 52 p.

72. Khmelovsky G.L., Krol O.S., Surnin Yu.M. Basics of process design automation. Tutorial. – K.: UMK VO, 1989. – 188 p.

73. Romanov V.F. Calculation of gear tools. – M.: Mashinostroenie, 1969. – 201 p.

74. Krol O.S., Sokolov V.I. 3D Modeling Of Machine Tools For Designers. – Sofia: Prof. Marin Drinov Academy Publishing House of Bulgarian Academy of Sciences, 2018. – 140 p. https://doi.org/10.7546/3d_momtfd.2018

75. Metal-cutting tools: Textbook for Universities in the specialties "Technology of mechanical engineering", "Metal-cutting machines and tools" / GN. Sakharov, O.B. Arbuzov, Yu.L. Borovoy and others – M.: Mashinostroenie, 1989. – 328 p.

76. Krol O., Sokolov V. Parametric Modeling of Machine Tools for Designers. Sofia: Prof. Marin Drinov Academy Publishing House of Bulgarian Academy of Sciences, 2018. – 112 p. https://doi.org/10.7546/PMMTD.2018

77. Krol O.S. Methods and procedures of 3D-modeling of metal-cutting machine tools and instruments. Monograph: Severodonetsk, EUNU, 2015. – 120 p.

78. Inozemtsev G.G. Design of metal-cutting tools. – M.: Mechanical Engineering, 1984. – 272 p.

79. Krol O., Belkov M. Study dynamics machining centre SF68VF4/ Teka Komisji Motoryzacji i Energetyki Rolnictwa, OL PAN, 2014, Vol.14, is.2, Lublin, Poland. – P. 59–67.

80. Krol O.S., Shevchenko S.V., Sindeeva E.V., Pokintelytsa N.I. Design of mechanical gears of metal-cutting machines with the help of a system APM WinMachine. Handbook. – Lugansk: Publishing House of Volodymyr Dahl East Ukrainian National University, 2007. – 200 p.

81. Krol O., Sokolov V. Rational Choice of Machine Tools for Designers. Sofia: Prof. Marin Drinov Academy Publishing House of Bulgarian Academy of Sciences, 2019. – 114 p. https://doi.org/10.7546/RCMTD.2019

82. Nefedov N.A., Osipov K.A. Collection of problems and examples for cutting metals and cutting tools / 5th edition, revised. and add. – M.: Mashinostroenie, 1990. – 448 p.

83. Krol O. Engineering Forecasting Of Machine Tools For Designers: monograph. – Sofia: Prof. Marin Drinov Academic Publishing House of Bulgarian Academy of Sciences, 2019. – 114 p. https://doi.org/10.7546/EFMTD.2019

84. Krol O. Selection of Machine Tools Optimal Cutting Modes for Designers. Sofia: Prof. Marin Drinov Academy Publishing House of Bulgarian Academy of Sciences, 2020. – 240 p. https://doi.org/10.7546/SMTOCMD.2020

85. Krol 0.S. Issledovanie shpindelnogo uzla mnogooperatsionogo stanka modeli SF16MF3. [Research of spindle node multioperation tool model SF16MF3]. – Visnik SNU. – [Bulletin of the SNU], 2014, 6, P. 121–125.

86. Krol O.S. Research of design and development of parametric and 3D models of a gear mill with a flange / Bulletin of the Skhidnoukrainian National University for the Name of Volodymyr Dahl, No. 4 (260), 2020. – P.34-39. https://doi.org/10.33216/1998-7927-2020-260-4-34-39

87. Shevchenko S., Mukhovaty A., Krol O. (2020) Gear Transmission with Conic Axoid on Parallel Axes. In: Radionov A., Kravchenko O., Guzeev V., Rozhdestvenskiy Y. (eds) Proceedings of the 5th International Conference on Industrial Engineering (ICIE 2019). ICIE 2019. Lecture Notes in Mechanical Engineering. Springer, Cham. pp. 1-10. https://doi.org/10.1007/978-3-030-22041-9_1

88. Shagun V.I. Cutting tool. Foundations of design theory. – Minsk: Design PRO, 1998. – 112 p.

89. Krol O.S., Shevchenko S.V., Sokolov V.I. Design of metal-cutting tools in the middle of APM WinMachine. Textbook. – Lugansk: SNU, 2011. – 388 p.

90. Krol O.S., Osipov E.I., Krol A.A. Simulation of IT-1 machine tool drive in APM WinMachine environment/Bulletin of Volodymyr

Dahl East Ukrainian National University. – Lugansk: SNU, is. 2 (191). Part 1, 2013. – P.112–115.

91. Krol O.S., Krol A.A. Simulation of the multi-purpose lathe spindle node in the APM WinMachine environment/Machine tool reliability and optimizing technological systems. Collection of scientific papers. – Kramatorsk: vol. 26, 2010. – P. 112–117.

92. Lieberman A.I. Calculation of multi-blade tools using the copy method. – M.: Mashgiz, 1962. – 360 p.

93. Zamriy A.A. Practical training course CAD/CAE APM WinMachine. Teaching manual. – M.: Publishing house APM, 2007. – 144 p.

94. Krol O.S., Krol A.A. Building spindle models of a multi-purpose lathe in the APM WinMachine environment/Bulletin of Volodymyr Dahl East Ukrainian National University. – Lugansk: SNU, is. 3 (145). Part 2, 2010. – P.143–148.

95. Krol O.S., Krol A.A. Using CAD ARM WinMachine in the tasks of the study of toothed belt drives. – Lugansk: Publishing House of Volodymyr Dahl East Ukrainian National University, 2012, is. 13 (184). – P. 147–153.

96. Krol, OS., Krol, A.A., Sindeeva, E.V. Modeling of the design of the four-shaft in the CAD APM "WinMachine"/Resource-saving technologies of production and processing of materials in mechanical engineering/ Collection of scientific papers. – Lugansk: Publishing House of Volodymyr Dahl East Ukrainian National University, 2008. – P. 139–143.

97. Shelofast V.V., Chugunova T.B. Basics of designing machines. Examples of problem solving. – M.: Publishing house APM, 2004. – 240 p.

98. Krol O.S., Krol A.A., Andriyko, A.A. Parametric modeling of V-belt and poly-V-belt pulleys in the APM Graph module//Progressive directions for the development of machine-tool-making industries and transport. Materials of the international scientific and technical

conference of students, graduate students and young scientists. – Sevastopol: Publishing house SevNTU, 2010 – P. 165–166.

99. Nikolaev A., Sokol I. Module APM Base – effective work with databases / CAD and graphics, is. 1, 2005. – P. 42–49.

100. Krstić, B., Krstić, M. (2016). Rational choice theory and Social Research. Sociologija, 58 (4), 598-611.

101. Nerubaschenko, A.A., Krol, O.S., Krol, A.A. Creation of a database of parametric models for machine parts in the APM Base module // Bulletin of SevNTU, 2010, is. 107. – P.107-109.

102. Krstić, M. (2012). The role of rules in the evolution of the market system: Hayek's concept of evolutionary epistemology. Economic annals, 57 (194): 123-140.

103. Rozinsky S., Shanin D., Grigoriev S. Parametric capabilities of the graphic module APM Graph of the APM WinMachine system. CAD and graphics, is. 11, 2001. – P. 37–40.

CONTENT