Influence of the cross-sectional area of the shear layer on the distribution of the zones of tension and compression in replaceable cutting inserts

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Abstract. As a result of the conducted researches it is established that with a progressive cutting scheme, the dangerous tensile stresses in the cutting carbide plates are significantly reduced. It was found that when using a worm cutter with a progressive cutting circuit, the dangerous tension of the tensile stresses on the front surface of the carbide plates is greatly reduced. Analysis of the obtained main stresses in the cutting wedge showed that the cutting edge experiences tensile stresses on the front surface, and compression on the front surface. It is established that the cutting element of the milling cutter undergoes an alternating asymmetrical nature of loading, accumulating cyclic fatigue in the main cutting edge.

Key words: gear milling, hard alloy, prefabricated worm cutter, stress-strain state of cutting elements.

1. Introduction
The instrumental equipment plays an important role in the work of machine-building enterprises. One of the most important elements of tooling is the cutting tool [1]. The replacement of the tool with replaceable multi-sided plates of the hard alloy [2, 7, 13, 14, 16] gives an increase in productivity and overall processing efficiency [8-12, 15, 17-21]. Carbide cutting tools are designed for high-speed cutting of gears from structural and hard-to-work steels and alloys, cast iron, non-ferrous metals and various non-metallic materials. The tool material must have high cutting properties. The best material that meets these requirements is a metal-ceramic alloy of various grades. Hard alloys used to equip a gear cutting tool that works with intermittent cutting with cyclic, dynamic and thermal loads, in addition, must have a high endurance limit. The physicomechanical and, of course, the operational properties of various hard alloys depend on the chemical composition and the size of the grains [22-27, 30]. Alloys with lower cobalt content have greater hardness and heat resistance, and allows for high cutting speeds. However, a decrease in the cobalt content increases the brittleness of the alloys and reduces the strength, so different groups of alloys are used depending on the operating conditions of the tool.

2. Gear milling with different types of feeds
Gear milling with radial-longitudinal feed, as shown in figure 1, consists in the fact that the worm cutter moves radially at the beginning of the cutting and until the total tooth height is reached, after which the longitudinal feed is turned on, at which the teeth of the wheel are cut.
To implement this method, standard worm cutters and special hobbing machines are used which have a mechanism for automatically switching the feed from radial to longitudinal at precisely fixed interaxial distance. The method is used to shorten the infeed length, i.e. for the replacement of longitudinal infeed by radial. At the same time the cutting time is reduced to 30%. In addition, with radial gear milling, the following advantages are most noticeable:

- with equal productivity, the wear of the teeth, the cutting cutter, operating with radial incision is 1.5-2 times smaller than with the longitudinal cutter. This is facilitated by the best cutting scheme, which provides, on the one hand, a more favorable shape of the slices, and on the other hand, and more in the length of the tooth-milling contact with the metal, which makes the hobbing machine smoother, especially at the beginning of the cut;

- when the diameter of the cutter is increased, the length of the working radial feeds remains constant, which is very important for the use of large diameter worm cutters.

The use of the method is limited by the permissible tool load, the radial feed, less than the longitudinal feed $S_0 - S_{p} = 0.5 \ldots 0.75 \times S_0$, and cutting power, since it is much larger in radial incision than in the case of longitudinal cutting (when cutting spur gears, the largest cutting powers are about equal If the feed ratio is within $1/4 < S_{p} / S_0 < 1/3$).

We also consider the cutting of worm wheels and cylindrical helical gears in the implementation of radial and tangential feeds. When cutting worm wheels, the axis of the cutter is set perpendicular to the axis of rotation of the workpiece, as shown in Figure 1.8, while the machine must be provided with the basic movements: the main rotational motion of the milling cutter $V$; rotational movement of the product (workpiece) $V_3$; the motion of the radial feed $S_p$ as shown in Fig. 2a. The radial feed stops when the full depth of milling is reached. Figure 2b shows how, with the tangential feed $S_m$, the milling cutter is immediately set to the full depth of the milling, and the cutter is inserted into the workpiece.

The method of gear. However, with this method, the number of cuts is relatively small and, therefore, high accuracy is not achieved. In addition, with a radial feeder, the cutter operates only with the small portion of his line, and with the wearer's out unevenly; this also affects the accuracy of the tooth of the cut wheel.

When cutting cylindrical wheels, the worm cutter is installed in such a way that the turns of the milling cutter are facing the workpiece when machining the wheels with straight and oblique teeth. 3a, b. If the direction of the turns of the milling cutter and the teeth of the gear to be cut is the same, that is, both right or both left, then the spindle axis must be rotated through the angle $eta - \beta_1$ to the horizontal, where $\beta$ is the angle of inclination of the gear teeth to its axis, $\beta_1$ is the angle of the helical cutters as shown in Figure 3. Figure 3b shows that the directions of the cut. In this case, then the axis of the spindle (milling cutters) must be turned in the vertical plane by the angle $\beta + \beta_1$ to the horizontal.

Conventional worm-type cutters designed for cutting worm wheels using the radial feed method, wear out on the back surface during operation. After refinishing them on the front surface, the diameters
of the cutter are reduced, which means that the distance between the axes of the cutter and the cut wheel is different from that of the worm and the wheel when they are mounted, so that the quality of the engagement of the worm pair.

![Diagram](image1)

**Figure 2.** Screwing of the worm gear teeth:
a - by means of radial feed; b - using tangential feed

![Diagram](image2)

**Figure 3.** Cutting of oblique teeth on a cylindrical wheel:
a - the directions of the turns of the milling cutter and the workpiece are the same; b - the directions of the turns of the mill and the workpiece are different

At the diagonal gear, the milling machine, the worm milling machine, is the one informed of the two cuts, and the other one.
Figure 4 shows a schematic diagram of a tooth cutting using a diagonal feed, when the whole length of the worm cutter is used to cut each wheel or pack of wheels.

Figure 4 Diagonal gear milling scheme:
1) inclined ruler; 2) the workpiece to be processed; 3) worm cutter

The amount of vertical feed is selected according to the normative data, the quantities Lp and B are known. The necessary ratio between the rotation of the mill and the workpiece, caused by the axial movement of the mill, is provided by tuning the differential and diagonal feed guitar. In the case of diagonal gear milling, almost all the teeth of the mill are involved. This makes it possible to switch to an increase in the cutting speed, and to reduce the machine cutting time of the gear wheel. For the implementation of diagonal gears, milling, it is necessary to equip the gears, hobbing machines with universal calipers. Examples of such machines, equipped with universal calipers, can be called domestic gear hobbing machines model 5K324.

3. Application of hard alloys for gear milling

Carbide cutting tools are designed for high-speed cutting of gears from steels and alloys, cast iron, non-ferrous metals and various non-metallic materials with increased abrasive properties, such as astextolite, polyamide resins, capron etc. [31-35, 43].

Carbide-tipped tools are used for machining cogwheels in instrumentation, automotive and tractor engineering, machine tools and other industries. The carbide tools are machined with gears of 0.2-10 mm modules. Along with the processing of cogwheels of low and medium hardness, hard alloy tools.

Carbide cutting tools are rationally used in large-scale and mass production. The use of hard-alloy gear- cutting tools in small-scale and single-piece production is justified only if a tool of tool steel cannot be used at all [36-42, 44, 45].

The tool material must have high cutting properties. The best material that meets these requirements is a metal-ceramic alloy of various grades. Hard alloys used for cutting tools, that is, with, intermittent, cutting with cyclic, dynamic and thermal loads, in addition, must have a high endurance limit, not broken by stress.

The physico-mechanical and, because of, the operational properties of various hard alloys. Alloys with lower cobalt content have greater hardness and heat resistance, and allows for high cutting speeds. However, a decrease in the cobalt content increases the brittleness of the alloys and reduces the strength, so different groups of alloys are used depending on the operating conditions of the tool. Table 1.
| Hard alloy | Operational properties | Application area |
|-----------|------------------------|------------------|
| VK3M      | High wear resistance, moderate operational strength, resistance to shocks, vibrations and chipping. | Finishing and semi-finished machining of gear parts from gray cast iron, hardened steels, hard cast irons, non-ferrous metals and their alloys, plastics, etc. |
| VK6M      | Wear resistance is VK6, with slightly lower operational strength and resistance to shocks, vibrations and chipping. | Gear milling with small-milling cutters of parts from carbon and alloy steels, heat-resistant steels and alloys, stainless steels of austenitic class, special hard cast iron, hardened cast iron, hard bronze, light metal alloys. Shearing of steel hardened gears with hardness up to HRC 45-50, cutting of conical wheels with circular teeth. |
| VK8       | High operational strength and resistance to shocks, vibrations and chipping as compared to the performance properties of VK6 alloy with lower wear resistance and allowable cutting speed. | Drafting of parts made of cast iron, nonferrous metals and alloys and non-metallic materials, special hard-to-process heat-resistant steels and alloys, shaving of hardened gears and gears from hard-to-process steels and alloys. |
| VK10      | High operational durability, good resistance to shocks, vibrations, chipping. | Roughing and finishing of cogwheels of cast iron, non-ferrous metals and hardened steels by milling and shaving. |
| VK15      | High operational strength and toughness | Roughing and finishing of cogwheels from cast iron with intermittent impact cutting (mainly when gearing). |
| T30K4     | The highest wear resistance and permissible cutting speed for titanium-tungsten alloys with reduced operational strength and resistance to shocks, vibrations and chipping. | Pure gear-milling with small sections of shear from non-hardened and hardened carbon and alloyed steels. |
| T15K6     | High wear resistance and allowable cutting speed with greater operational strength and resistance to shocks, vibrations and chipping. | Draft, semi-finished and final gear milling of parts made of carbon and alloyed steels. |
| T14K8     | The operational strength and resistance to shocks, vibrations and chipping is higher than the performance properties of the T15K6 alloy with less wear resistance and allowable cutting speed. | Drafting and semi-trimming of parts from carbon and alloyed steels. |
| T5K10     | The operational strength and resistance to shocks, vibrations and chipping is higher than the performance properties of the T14K8 alloy. | Roughing of coarse-grained gear wheels from carbonaceous and alloyed steels. |
| Hard alloy | Operational properties                                                                 | Application area                                                                 |
|------------|-----------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| T5K12V     | The operational strength and resistance to shocks, vibrations and chipping is higher than the performance properties of the T5K12B alloy with less wear resistance and allowable cutting speed. | Pre-gear milling and chiseling of parts from carbon and alloy steels.              |
| TT7K12     | The operational strength and resistance to shocks, vibrations and chipping are significantly higher than the performance properties of T5K10 alloy with less wear resistance and allowable cutting speed. In comparison with the alloy, T5K12B has a somewhat higher operational strength. | Gear milling and chiseling of parts from carbon and alloy steels.                  |
| TT10K8B    | High operational strength and resistance to shocks, vibrations and chipping with moderate wear resistance. | Draft and semi-finished milling of parts from hard-to-work materials, including heat-resistant steels and alloys. |
| TT20K9     | With the same properties as the T14K8 alloy, it has a higher resistance to shocks, vibrations and chipping, allows an increased feed rate at the same cutting speed. | Drafting and semi-trimming of parts from structural steels and non-ferrous metal alloys. |

As the size of the grains of tungsten carbide decreases, the hardness of the alloy increases, and strength decreases. So alloys VK6 (grain size of tungsten carbide 1-2 μm) and VK6M (grain size of tungsten carbide up to 1 μm) have the same chemical composition, but the hardness of the alloy VK6M HRA 90, and the hardness of alloy VK6 HRA 88.5; the strength of bending of alloy VK6 is not less than 150 kg / mm, and the alloy VK6M 135 kgs / mm.

Alloys of the OM group (especially fine-grained) of VK6-OM, VK10-OM and VK15-OM grades, in which the grain size of tungsten carbide does not exceed 0.5 μm, are intended for processing stainless, heat-resistant and other hard-working steels and alloys.

4. Advantages and disadvantages of assembly tools with RMP

Removable Multifaceted Plates - RMP are used in prefabricated chisels, drills, countersinks, cutters, broaches. Various methods of fastening the RMP in the cutting tool body are used. According to the (All-Russian Scientific Research Institute) instrument, the experience of introducing domestic incisors with RMP has shown advantages in comparison with weld tool: an increase in the resistance of the plates by 25-30%, a decrease in the consumption of a hard alloy by a factor of 2, a reduction in the total cost of tooling by 3-4 times, an increase in labor productivity as a result of a reduction in the auxiliary time by 20-25%.

These advantages provide a reduction in the share of the tool with the tie-down plates. For example, at the Volga automobile plant, the proportion of turning incisors with brazed plates is 24%. Widely used prefabricated cutting tools at the Kama Automobile Plant and a number of other factories. According to the catalogs of the cutting tools of foreign firms, there is almost no tool with tungsten carbide inserts. In these catalogs various designs of the cutting tool with mechanical fastening RMP are given, designed for processing structural and alloy steels, as well as high-strength hard-to-work materials. Especially effective is the use of the cutting tool on the machines with computer numerical control (CNC), if the instrument after changing RMP or its rotation does not require additional adjustment and adjustment.

The efficiency of metalworking will increase when creating a special cutting tool by using RMP, not used in standard tools. To such RMP plates with back corners, with chip breaker grooves on both sides, and an increased degree of accuracy, should be assigned to achieve a high accuracy in positioning...
the vertex of the plate when it is rotated or changed. Recently, the nomenclature and release of RMP have been expanded, various designs of tools with mechanical fastening RMP have been developed. Application of cutting tools with RMP eliminates the soldering of the plates, sharpening and re-sharpening, which makes it possible to effectively use scarce alloying elements of hard alloys, since up to 90% of the amount of RMP after use is returned to recycling.

The change of plates leads to a reduction in the number of holders, which reduces the number of tools in circulation by 2-3 times and provides a saving in materials. Rotate and change RMP shortens auxiliary time.

Despite a number of the above advantages of the composite cutting tool, today its wide application limits some difficulties arising in the calculation, design or choice for a specific type of processing.

With a very large variety of shapes and types of plates, as well as the structure of the holders, there is not enough systematized material for the specific use of certain forms of plates, this or that design of the holder in specific conditions. In addition, there are difficulties in choosing the optimal geometric parameters and obtaining them on the tool by setting the plate in a certain position in the tool body, taking into account also that it itself has geometry in the delivery state.

Carbide-tipped worm cutters with sharpened cutting elements have some drawbacks. Teeth cutters with angles of sharpening less than 90˚ do not ensure the reliability of the milling cutter when cutting steel gears due to frequent chipping of the outer and transitional cutting edges. Cutting teeth of mills are subject to stresses and cannot be treated qualitatively with diamond abrasive grinding wheels. The grinding of the teeth of such cutters on the rear surfaces must be carried out every time after the appearance of permissible wear. These drawbacks exclude the use of pivoting perishable plates of a hard alloy as the cutting part of worm mills. Rotary perishable plates with angles of sharpening 90˚ and more are made of wear-resistant hard alloys, such as alloy T15K6. They can be processed with diamond grinding wheels.

5. Simulation modeling for worm mills

The method of graphical simulation of the process of gear milling is to visualize the cutter during its operation. This gives us the opportunity to follow the route of machining the wheel with a milling cutter, as a result of which it is possible to obtain a cross section of the cut layer. The size of the contact spots will show us which plates are loaded more than others. In order to graphically simulate the process of gear milling, it is necessary to correctly place the cut wheel and cutter in the space (in the drawing).

In order to justify my assumption of the maximum efficiency of the progressive cutting scheme, a so-called "simulation modeling" of the gear milling process of the gear wheel (simulation of wheel running was carried out in the "Compass V 13" program with the subsequent entry of the measured areas into Excel tables).

For the sample for comparison was taken the usual full-profile worm cutter (the number of teeth on the rail = 7, the number of rails = 8). Parameters of the cut gear: module 5, number of teeth 30, divisible diameter 150 mm. Feed the cutter vertically and then gradually insert the teeth into the workpiece as shown in Figure 5.
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1) draws a circle equal to the path of movement of the 1st wafer at gear milling, this circle is denoted by the letter B;
2) We draw a sketch wheel with the designation wheel center;
3) Postpone the center-to-center distance of the milling cutter-wheel $A_c$;
4) We have circle B on the distance $A_c$ from the center of the wheel;
5) In height, we have circle B so that it touches the profile of the wheel, but does not cross it;
6) Choose the flow per turnover $S$ (mm / tur). Feed mills selected from design considerations. The front working surface of the plate has a limited height. It is necessary to measure the height and take delivery less. In my case, feed per turnover was selected $S = 2.5$ (mm / tur).
7) Postpone the amount of feed $S$ from the center of the circle down, until the last feed will not be in one plane with the wheel.
8) Begin to move the circle along the vertical axis of the wheel by an amount $S$. In this way, we will simulate the process of feeding the cutter. To fix the position of the circle with each move to the feed $S$, we need to draw a vertical line at the intersection of the circle and the wheel, which will symbolize the amount of cutting the cutter into the workpiece on one pitch.
9) As a result of such movements, we get traces left by the circle on the wheel, received for all feeds. This provision shows us that the mill ran into the wheel completely. Further advancement of the cutter along the cut surface of the wheel will also be carried out by feeding, but this is not important to us, because we have already obtained the necessary lines for the further graphical construction (plunging values).
10) Next, we need to find the angular step of turning the wheel $S_k$. This value characterizes the rotation of the wheel at some angle when inserting into the body of the next plate on the account.

$$S_k = \left( \frac{S_o}{z} \right) \cdot \frac{N}{n - 1}$$  \hspace{1cm} (1)

Where the $z$ - the number of gear teeth;
$N$ - number of turns of the cutter;
n - number of plates in the turn.
In my case:
\[ S_K = \left( \frac{360}{30} \right) \cdot \frac{7}{8-1} = 12^\circ \]

11) on the tooth feed is calculated as follows:

\[ S_K = \frac{S_\delta}{z_\delta} \]

where \( S_\delta \) - feed per tooth mm / rev;
\( z_\delta \) - number of teeth on the coil.

\[ S_K = \frac{2.5}{8} = 0.3125 \text{ mm / tooth} \]

In the process of running-in, the cross sections of the cut-off layer of the front surface of each tooth were measured. Maximum loads such teeth are tested when cutting into the workpiece. The cutting forces for gear milling are directly dependent on the area of these spots. Based on the results of the obtained data on the cross sections of the cut layer, plots of the dependence of the area of the cut layers on the vertical movement of the tool were plotted.

**Figure 6.** Fragments of areas of tooth contact spots of a full-profile milling cutter.

Figure 6 shows the fragments of simulation modeling for a full-profile milling cutter. It can be seen that the tooth works simultaneously both in the upper and lateral edges. As a result, a complex three-element shavings is formed, the shape of which hinders its favorable descent.
Figure 7 shows the dependence of the areas of the cut layers on the cutting depth. It can be seen that the teeth No. 3 and No. 4 are the most loaded. The maximum cross-sectional area of the sheared layer is 2.8 mm² (tooth No. 4). The load of tooth No. 4 reaches a maximum in the middle of the cutting (feed No. 80-90). Tooth No. 3 is loaded more evenly, the maximum cross-sectional area of the sheared layer is 1.5 mm². Teeth No. 2 and No. 5 are less loaded, the maximum areas are 1 and 1.2 mm², respectively.

a, b - an imitation model for the lowered initial contour of the tool rack (e1),
c, d - imitation model for the narrowed initial contour of the tool rack (e2)

**Figure 8.** Simulation simulation of gear milling with a milling cutter with progressive cutting scheme

The second simulation was performed for the progressive milling cutting scheme shown in Figure 8.

![Simulation simulation of gear milling with a milling cutter with progressive cutting scheme](image)

**Figure 9.** The cross-sectional fragments of the shear layer cutter cutting teeth with a progressive scheme.

Figure 9 presents the cross-sectional fragments of the shear layer for the progressive milling. Simulation shows that the progressive working different parts of the teeth - one tooth cut into the upper edge, the other - side. As a result, the separation of chips on the side, which facilitates its descent, reduces the load on the tooth edge and, as a result, the cutting force.

Progressive geometry calculate slats cutter. Progressive teeth differ from full-profile on the corresponding values of overstatement $e_1$ and constricted $e_2$. The dimensions $e_1$ and $e_2$ are selected depending on the module, the number of teeth to be cut and the number of entries wheel cutters. Nominal overestimation $f_1$ for a single-pass milling with module 5 is 0.2 mm, the nominal narrowed $e_2$ for the same rack equal 0.15 mm. The values of $e_1$ and $e_2$ are obtained on the basis of theoretical and experimental studies with hobbing wheel module 2...2.5 mills with a number of teeth $z_0 = 12$ and module 2.5...10 mm $z_0 = 10$. When the number of teeth different from these values, table values $f_1$ and $f_2$ must be multiplied by the correction coefficient $K'$, which is considered the formula (for cutters with a modulus of 2.5...10 mm):
\[ K' = \frac{10}{z_0} \]  

where \( z_0 \) - number of teeth on cutter coil.
In this case:
\[ K' = \frac{10}{8} = 1.25 \]

In accordance with the correction coefficient values of \( e_1 \) and \( e_2 \) will be equal to:
\[ e_1 = 0.20 \cdot 1.25 = 0.25 \text{ (mm)} \]
\[ e_2 = 0.15 \cdot 1.25 = 0.1875 \text{ (mm)} \]
The height of the tapered teeth is adopted in accordance with the GOST "Worm cutters single-threaded" and will equal for the module 5 equal to 12.5 mm.
Height underestimated teeth calculated by the formula:
\[ h = h_b - e_1 \]  

\[ h = 12.5 - 0.25 = 12.25 \text{ (mm)} \]

The width of the low tooth accepted standard (GOST "single-pass mills worm"). Module 5 tooth width \( S_n = 8.02 \text{ mm} \).
The width of the inflated teeth will be equal to:
\[ S_b = S_n - 2e_2 \]  

\[ S_b = 8.02 - 2 \cdot 0.1875 = 8.02 - 0.375 = 7.645 \text{ (mm)} \]

According to the results of calculations starting circuits have been designed rails for the progressive scheme of cutting shown in Figure 10.

Figure 10. Geometry rails designed cutters with cutting progressive scheme.
a - the cross sectional area of the shear layer of the front surface of the cutting insert lowered rack-type tool initial \((e_1)\),
b - the cross sectional area of the shear layer of the front surface of the cutting insert constricted rack-type tool initial \((e_2)\)

**Figure 11.** Diagram of the transverse cross section of the shear layer with progressive cutting pattern

According to the results of the work schedule of the teeth shown in Figure 11, changes in progressive milling are seen in comparison with the full profile. The load on the teeth is reduced, the teeth are loaded more evenly. The maximum load on tooth No. 4 is shifted closer to the beginning of milling (the cross-sectional area of the cut-off layer is 1.9 mm²). The maximum cross-sectional area of the cut-off layer of tooth No. 3 is 1.4 mm². Teeth No. 2 and No. 5 are less engaged than in the full-profile cutting scheme, the cross-sectional areas of the cut-off layers for these teeth do not exceed 0.4 mm².

6. **Modeling of Finite Element Method**
In the articles [13-14, 16, 17] the stress-strain state in the teeth of the cogwheel is considered. And what happens in the cutting wedge carbide plate worm cutter is not considered. The analysis of two graphs of the cross-sections of cut layers for a full-profile and progressive milling scheme is given in [15]. According to this, the following conclusions are drawn: with full-profile milling, the loading of the cutting elements gradually increases to the middle of the infeed, and then decreases towards the end of the cutting, then with the progressive cutting scheme, the maximum The areas of the cut layers are at...
the very beginning of the cutting. In this case, the load on the cutting elements in the progressive scheme is more uniform, which is favorable for the design of the tool; With progressive cutting, the cross-sectional area of the sheared layer is reduced in comparison with full-profile cutting. The maximum cross-sectional area of the cut-off layer for a full-profile milling cutter is 2.85 [mm²], for a progressive cutter 1.9 [mm²]. Reducing the cross-section (a, respectively, and the load on the teeth) also helps to reduce the wear of the cutting edges of the teeth; In the progressive cutting scheme, the teeth No. 3 and No. 4 are more involved, and the teeth No. 2 and No. 5 are almost unloaded, in comparison with the full-profile scheme.

7. Test task of power loading
The test problem for optimizing the finite element mesh and the effect of the grid density on the calculations and the results of the stress-strain state in the cutting inserts using the ANSYS software are given. Further, the specification of the boundary conditions for the most stressed moments of gear milling under various gear milling schemes is shown.

For the possibility of applying a numerical solution, it is necessary to split the geometric models by a finite element mesh.

In order to apply the finite element method in the future, it is necessary to solve the test problem for constructing a grid model with the optimal grid resolution. To do this, in the active window of the ANSYS program for the beginning, the model was split into finite elements in the automatic mode. This is done in order to reduce errors in the construction of a finite element mesh.

Further, in order to find the optimal grid density in the 3-D model, the Relevance operation was done, as shown in Figure 12. To do this, you should choose a grid density factor that can be set from -100 to +100. When the model is broken in automatic mode, the density of the grid is 0. That is, this method of finding the optimal grid density provides good opportunities for solving the test problem.

![Figure 12. Schematic representation of the change in grid density](image)

Further in Figure 13, three-dimensional models of carbide-tipped plates working according to the standard cutting scheme are shown. It is in this cutting scheme that the cross-sectional area of the cut-off layer from the front surface of the cutting insert has the largest values with different densities of the finite element mesh.
Then the plate was loaded along the largest contact area along the front surface with various grid density variations and the most dangerous tensile stresses ($\sigma_{1\max}$) were considered, as shown in Figure 13. Then the largest tensile stresses ($\sigma_{1\max}$) were taken and the deviation in% was considered for each factor of grid density.

**Figure 13.** Various mesh density
\[ \sigma_{1\text{ max}} = 1.62 \text{ Pa at mesh density } = 0 \]
\[ \sigma_{1\text{ max}} = 1.59 \text{ Pa at mesh density } = +20 \]
\[ \sigma_{1\text{ max}} = 1.8 \text{ Pa at mesh density } = +40 \]

\[ \sigma_{1\text{ max}} = 1.79 \text{ Pa at mesh density } = +60 \]
\[ \sigma_{1\text{ max}} = 1.87 \text{ Pa at mesh density } = +80 \]
\[ \sigma_{1\text{ max}} = 1.82 \text{ Pa at mesh density } = +100 \]

**Figure 14.** Effect of mesh density on the value \( \sigma_{1\text{ max}} \)

When constructing a grid model, it is necessary to search for the optimal discreteness of the grid, taking into account the accuracy of the calculations. A grid with a large number of nodes allows you to find a more accurate solution. Errors are not reduced to zero, because with the increase in the elements, rounding errors in the computer accumulate. Ideally, the solution should not depend on the density of the grid. Grinding the grid does not compensate for the assumptions of the physical model and the error in the input data.

To calculate the deviations at different densities compared pairwise grids \( \sigma_{1\text{ max}} \) at 0, +20, +40, +60, +80, +100 mesh density factors.

When calculating the deviation in\% at 0 and +20 mesh density deviation \( \Delta \sigma_{1\text{ max}} = 2\% \)
When calculating the deviation in\% at +20 and +40 mesh density deviation \( \Delta \sigma_{1\text{ max}} = 11.7\% \)
When calculating the deviation in\% at +40 and +60 mesh density deviation \( \Delta \sigma_{1\text{ max}} = 0.5\% \)
When calculating the deviation in\% at +60 and +80 mesh density deviation \( \Delta \sigma_{1\text{ max}} = 4.3\% \)
When calculating the deviation in\% at +80 and +100 mesh density deviation \( \Delta \sigma_{1\text{ max}} = 2.7\% \)

It was decided to take automatic reception finite element mesh in automatic mode by a factor equal to the density of 60, as deviation of 0.5%.

Further, three-dimensional models of plates with cross-sectional areas of cut layers are constructed with a front surface of the plate with a distributed load assignment and embedments under the conventional gear-milling scheme (Figure 15).
Further, three-dimensional models of plates with cross-sectional areas of cut layers are constructed with the front surface of the plate with the assignment of distributed load and sealing with the progressive gear-milling scheme (Fig. 16).
The obtained patterns of directions of stress vectors at the nodal points with the aid of the ANSYS computational complex made it possible to construct a redistribution of the zones of extensions and contractions in the RCI (replaceable cutting insert).

**Figure 16.** Distributed load and termination in the conventional gear-milling scheme
Patterns of directions of vectors at the nodal points of the cutting wedge RCI made it possible to construct trajectories of zones of stretching and compression in the cutting wedge, according to which it is possible to predict the nature of fracture as shown in Figures 17 and 18. It can be seen that in the teeth of the standard worm cutter there are enlarged zones of extension.

**Figure 17.** Distribution of tensile and compression zones in the cutting wedge of the tooth in the plane of the chip shavings of a standard worm cutter
Figure 18. Distribution of tensile and compression zones in the cutting wedge in the plane of the chip shavings of the cutter with a progressive cutting scheme
In the teeth of the milling cutter, operating according to the progressive cutting scheme, there is a decrease in the stretching zones, which positively affects the reduction of the stress-strain state of the RCI. A comparative analysis of the trajectories of the zones of stretching and compression showed that the destruction along the front surface will occur by detachment, and along the rear surface by a shear. Analyzing the patterns of directions of stress vectors at the nodal points, it was established that the cutting element of the milling cutter undergoes an alternating asymmetrical nature of loading, accumulating cyclic fatigue in the main cutting edge. The number of loading cycles corresponds to the number of slips in the workpiece. Analysis of the obtained patterns and isolines of the main stresses in the cutting wedge of the RMP showed that at the time of the incision, the cutting edge undergoes a comprehensive compression, as the angle increases on the front surface, tensile stresses increase, and compression compresses at the rear. At the time of separation of chips from the workpiece, a sudden redistribution of stresses occurs: a compression zone is formed on the front surface, and stretches on the rear surface.

8. Surfaces of equal stresses $\sigma_1$ of standard milling cutter and milling cutter with progressive cutting scheme

Figure 19 shows the fracture surfaces (surfaces of equal dangerous tension stresses $\sigma_1$) in the teeth of a standard cutter.
Figure 19. Surfaces of equal tension stresses $\sigma_1$ of a standard mill

Figure 20 shows the fracture surfaces (surfaces of equal dangerous tension stresses $\sigma_1$) in the teeth of a worm cutter with a progressive cutting scheme.

Narrowed by an amount $e_1$

Underestimated by an amount $e_2$

Narrowed by an amount $e_1$

Underestimated by an amount $e_2$
Figure 20. Surfaces of equal tensile stresses $\sigma_1$ of a milling cutter with a progressive cutting circuit.

An analysis of the character on the basis of the ultimate tooth fracture surfaces of the milling cutter has shown that fracture occurs according to certain laws, and the fracture trajectories in the plate extend beyond the cross-section of the cut layer. In a numerical study, it is established that the nature of the fracture surface along the contour of the fracture trajectory in the cutting wedge along the front surface indicates brittle fracture by separation, and as the fracture surface approaches the main cutting edge, the process takes the form of plastic fracture.

Figure 21. Limit curves of contours of trajectories of failure surfaces.
Figure 21 shows the following regularities in the variation of the limiting surfaces as a function of the value of the parameter \( \chi \): as the transition to more brittle materials reduces the value of \( \chi \). The boundaries of the surfaces of the limiting stresses of the states, and, respectively, of the resolution surfaces of the replaceable hard alloy plates must fit in the region of the surfaces bounded by trajectories \( \chi = 0.75 \) - a state close to plastic destruction, \( \chi = 0.25 \) - a state close to brittle fracture.

9. Conclusions
1. The solution of the test problems showed the possibility of applying the finite element method for calculating deformations and stresses in the RCI of the assembly tools with the accuracy permissible for engineering calculations.
2. Calculations showed that the use of a worm cutter with a progressive cutting circuit is more effective than a standard worm cutter due to the fact that the reduction of the stretching zones is observed. This causes the hanging of the replaceable cutting insert to hang.
3. Analysis of the obtained patterns and isolines of the main stresses in the cutting wedge of the RCI showed that the cutting edge experiences tensile stresses on the front surface, and compressions on the front surface.
4. It is established that the cutting element of the milling cutter experiences an alternating asymmetrical nature of loading, accumulating cyclic fatigue in the main cutting edge. The number of loading cycles corresponds to the number of slips in the workpiece.

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