24. Soleymani, M. M., Fooladi, M., Rezaeizadeh, M. (2016). Experimental investigation of the power draw of tumbling mills in wet grinding. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 230 (15), 2709–2719. doi: https://doi.org/10.1177/0954406215598801
25. Soleymani, M., Fooladi Mahani, M., Rezaeizadeh, M. (2016). Experimental study the impact forces of tumbling mills. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 231 (2), 283–293. doi: https://doi.org/10.1177/0954408915594526
26. Yin, Z., Peng, Y., Zhu, Z., Ma, C., Yu, Z., Wu, G. (2019). Effect of mill speed and slurry filling on the charge dynamics by an instrumented ball. Advanced Powder Technology, 30 (8), 1611–1616. doi: https://doi.org/10.1016/j.apt.2019.05.009

UDC 621.914.1
DOI: 10.15587/1729-4061.2020.208579

DEVELOPMENT OF THE SINGLE-SETUP MILLING PROCESS MODEL OF THE SHAFT SUPPORT NECKS AND CAMS

V. Kalchenko
Doctor of Technical Sciences, Professor*
E-mail: kalchenkovi@ukr.net
V. Kalchenko
Doctor of Technical Sciences, Professor*
E-mail: vvkalchenko74@gmail.com
N. Sira
PhD
O. Kalchenko
PhD, Associate Professor
Department of Finance, Banking and Insurance**
D. Kalchenko
Programmer
Genix Solutions LLC
Zakhysnykiv Ukrainy str., 9, Chernihiv, Ukraine, 14030
V. Vynnyk
PET TECHNOLOGIES
Liubetska str., 60-D, Chernihiv, Ukraine, 14000
V. Morochko
PJSC «CHEZARA»
Zakhysnykiv Ukrainy str., 25, Chernihiv, Ukraine, 14030
*Department of Road Transport and Industrial Engineering**
**Chernihiv National University of Technology
Shevchenka str., 95, Chernihiv, Ukraine, 14035

Three-dimensional geometrical modeling of the processes of allowance removal and shaping of support necks and cams of camshafts when milling with crossed axes of the tool and part is proposed. Single-setup milling of camshafts, which are widely used in automotive, tractor, shipbuilding and other industries, is carried out by a cutter with crossed axes of it and the part. The rotation angle of the cutter is selected from the condition of providing the required roughness of the treated surface and is regulated by the feed. At the same time, high processing productivity is provided by an increase in camshaft speed. A method of milling support necks and cams is developed, where the processing is carried out by a cutter, the height of which is less than the lengths of the processed surfaces. When processing the passage, the main allowance is removed by the end face of the quadrangular roughing carbide plate, and the finishing is carried out by the unloaded periphery of the cermet finishing plate. This allowance distribution increases the productivity and accuracy of processing, and the ability to rotate the roughing plate saves material and reduces the cost of processing. In the process of milling the curved surface of the camshaft cam, the depth of cut along the machined profile is always greater than the value of the removed allowance. This causes a decrease in the accuracy and productivity of processing. In order to eliminate this problem, it is proposed to stabilize the depth of cut and feed along the contour with uneven rotation of the part. The uniformity of the depth of cut and feed along the curved contour of the cam is achieved by simultaneous vertical and transverse movements of the cutter and uneven rotation of the camshaft. When milling the curved surface of the cam, the center of which does not coincide with the camshaft center, there is an uneven rotation of the latter and synchronous vertical and transverse movement of the cutter. When machining the cam section, the center of which coincides with the camshaft center, the cutter is given only rotation

Keywords: camshaft milling, crossed axes, camshaft cams, support necks

Received date 18.03.2020
Accepted date 14.07.2020
Published date 17.08.2020

1. Introduction

Modern automobile, tractor, shipbuilding and other machine-building industries are characterized by a wide range of products with curved working surfaces. Such surfaces include, in particular, camshafts, crankshaft necks, brake pads, etc.

The competitiveness of machine-building products is determined by the high surface accuracy of parts and productivity of their processing. In modern economic conditions [1], the achievement of high values of these indicators is impossible without the use of three-dimensional modeling of processing processes, which are the geometric basis of automated design systems [2].

One of the productive ways to process curved surfaces of cams is milling [3].

In the known methods of deep milling of curved surfaces, in order to ensure their high accuracy, processing is usually carried out in several passes. This increases machining time, reduces productivity and accuracy due to uneven tool wear.

The method of milling with crossed axes of the cutter and the part ensures uniform distribution of the allowance along the cutting edge of the cutter, increases the productivity and accuracy of processing due to uniform wear of the cutting edge of the tool. However, in the existing methods of milling with crossed axes of the tool and cylindrical surfaces of complex profile, there are no studies of the peculiarities of the processes of allowance removal and shaping in one-pass machining.

Therefore, ensuring high competitiveness of the method of processing cylindrical surfaces of complex profile in various branches of mechanical engineering requires increasing the accuracy and productivity of their processing, reduces the durability of tools.

Therefore, the development and study of three-dimensional models of the processes of allowance removal and shaping in single-pass milling of support necks and cams of camshafts with crossed axes of the cutter and part is an urgent task.

2. Literature review and problem statement

Kharkiv Machine Tool Plant «HarVerst» (Ukraine) processes camshafts on grinding machines with CNC models HSH3-57F2 and HSH3-33 [4]. When running the cam profile, the camshaft rotates, and the circle reciprocates in a horizontal plane passing through the axis of the part. Processing of support necks is carried out on circular grinding semiautomatic devices of models 3M152VM and 3K152VF20. Copying the profile of the support necks is carried out with an abrasive wheel with the height of the length of the treated surface. First, rough grinding is performed, followed by finishing and calibration. In this method of processing, the depth of cut depends on the position of the point of contact between the tool and the part and varies along the cam profile. That is the reason for the uneven distribution of the allowance along the tool profile, and hence, uneven tool wear. Also, the disadvantages include the fact that the processing of the cams and support necks is carried out on different machines, which reduces the accuracy and productivity of processing.

In order to increase the grinding efficiency and shaping accuracy of the camshaft cam profile, two grinding wheels of different diameters are used in [5]. A grinding wheel with a larger diameter is used for roughing, and with a smaller one – for finishing. However, this increases the cost of production.

In [6], an algorithm for smoothing velocity curves is developed to increase the accuracy of camshaft cam shaping. And in [7], to improve the accuracy of processing camshaft cams, a mathematical model is presented, which describes the relationship between the displacement of the center of the grinding wheel and the angular displacement of the camshaft according to the cam lift. A new strategy for optimizing the movement parameters of the part is proposed. However, the issue of ensuring uniform depth along the processed profile of the cam is not considered in [6, 7].

Single-setup processing of support necks and cams was carried out by the Junker company (Germany) [8, 9]. Processing of support necks is carried out by a narrow circle, the height of which is less than the length of the processed surface. Running of the processed surface of the cam is carried out in one turn due to reciprocating movement of the grinding wheel in the plane that passes through the axis of rotation of the tool and the camshaft. However, in the process of machining, the point of contact between the wheel and the cam leaves the specified plane, so that the allowance is removed unevenly, and, consequently, the accuracy and productivity of grinding are reduced.

Milling is widely used to process camshafts. Thus, the Japanese company Kataoka produces a wide range of cam milling machines for processing camshafts. And the German company Heller [10] produces HELLER RFN production systems for milling camshafts. Machining of cams is carried out by running in with a mill, the height of which is equal to the height of the cam. The presence of two milling units on the machines increases the productivity of processing. In order to reduce the impact of cutting forces on the machining accuracy, the workpieces are clamped and supported by two hydraulic clamping chucks. The disadvantage of these methods is the different depth of cut along the cam profile, which affects the tool life and the lack of high-precision single-setup machining.

In [11], a method of milling with an oriented tool is developed, when rough milling is carried out by the end of the tool tooth, and finishing – by its periphery. This increases the accuracy and productivity of processing. However, only cylindrical parts are considered in the paper.

In [12], a method of milling camshafts with a tool whose height is less than the cam length is presented. Single-setup camshaft cam milling is performed. However, the entire allowance falls on the peripheral part of the cutting tooth of the cutter, which causes its wear and reduces shaping accuracy.

The problem of high-precision machining of camshaft necks and cams can be solved by developing three-dimensional models of allowance removal and shaping processes in single-pass milling with crossed axes of the tool and part. The analysis of the developed models will promote the development of high-performance methods of milling cylindrical surfaces of complex profile with crossed axes of the tool and part.

3. The aim and objectives of the study

The aim of the study is three-dimensional modeling of the process of single-setup machining of the support necks and cams of the camshaft when milling with crossed axes of the tool and part.

To achieve this aim, the following objectives were set:

– to develop spatial models of the tool surface and camshaft surfaces when milling with the crossed axes of the cutter and part;

– to develop a general model of the process of milling camshaft support necks and cams with the crossed axes of the tool and part;

– to investigate the process of shaping accuracy when milling camshaft support necks and cams.

4. Development of spatial models of the tool surface and camshaft surfaces

The scheme of the process of milling the support necks and curved surfaces of the camshaft 1 cams with the cutter 2, rotated by the angle δ, is presented in Fig. 1.

Roughing and finishing of all camshaft surfaces occur at a single setup. In this case, the end face of the quadrilateral plate 3, made of hard alloy, performs rough processing, and the periphery of the plate 4, made of cermets, finishing milling and calibration.

Milling of the camshaft 1 begins with processing of the cylindrical surface of the support neck *A* (Fig. 1). The cutter 2 is rotated around the O_mZ_{m1} axis at an angle δ, which is selected from the condition of providing maximum removal of allowance with uniform loading of the end plate 3 of the cutter 2.

The presence of grooves between the support necks and cams makes it possible to feed the tool to the entire depth of cut and machine the camshaft surfaces to the passage. This increases the machining accuracy because the cutting forces are directed along the axis of the part in contrast to processing methods, where the tool is fed in the radial direction, which reduces the rigidity of the part and, accordingly, the accuracy of its shaping.

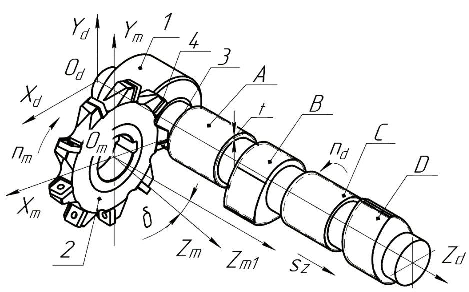

Fig. 1. Scheme of milling a camshaft with the crossed axes of the tool and part

The cutter is fed to the entire depth of cut *t* (Fig. 1) and moves along the O_dZ_d axis with the feed rate s_z, while the speed n_d of the camshaft when machining the support necks is selected under the condition of ensuring maximum machining productivity. The rough allowance is removed by the end face of the roughing plate 3 of the cutter 2, and finishing is carried out by the periphery of the finishing plate 4.

After machining the cylindrical surface *A* (Fig. 1) of the support neck, the cutter is moved in the vertical direction of the O_dZ_d axis to the height of the cam *B*, taking into account the allowance *t* and the process of machining the curved surface of the cam begins.

When milling the curved surface of the cam 6 (Fig. 2, *a*), the camshaft rotates unevenly with a frequency of n_{dc}. The cutter rotates with a frequency of n_m and simultaneously performs vertical and transverse movement S_m. Thus, the points of contact *A* and A_1 of the cutter 2 with the curved surface of the cam 6 are in the plane, passing through the rotation axis of the tool and the curvature center of the part. This, in turn, provides a constant depth of cut along the cam contour and uniform wear of the cutting inserts of the cutter.

When machining the cam section, the center of which coincides with the camshaft center (position *I*, I_1 in Fig. 2, *b*), the cutter 2 is given the rotation n_m. There is no need for vertical and transverse movements of the cutter. In contrast to the machining of cam sections, the centers of which do not coincide with the camshaft center (position *I*, I_1 in Fig. 2, *a*), where the cutter rotates and moves in transverse and vertical directions (position *II*, II_1 in Fig. 2, *a*).

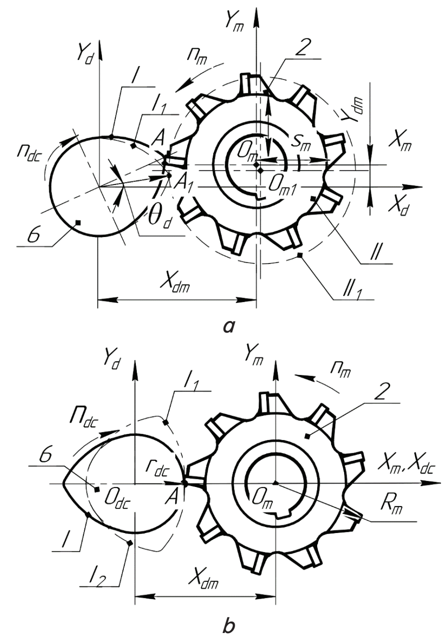

Fig. 2. Scheme of milling cam sections: *a* – processing of surfaces, the centers of which do not coincide with the camshaft center; *b* – processing of surfaces, the centers of which coincide with the camshaft center

After processing the cam *B* (Fig. 1), the neck *C* and cam *D* are processed successively according to the above-described technique.

Uneven circular feed of the camshaft with simultaneous vertical and transverse movements of the tool when milling curved surfaces on CNC machines eliminates the effect of cutter wear on shaping accuracy. This increases the accuracy of the curved surfaces of the cams, processing productivity, as well as simplifies the programming of processing, as there is no need to take into account the worn profile of the tool. Also, in the existing methods there is no vertical movement of the tool and there is a need to reprogram the machining process to take into account the worn geometry of the cutting surface of the tool to eliminate machining errors.

The spatial model of the tool surface is given by the product of single-coordinate displacement matrices M2, M3 along the Y_m and Z_m axes, respectively, and the rotation matrix M6 around the O_mZ_m axis (Fig. 1):

$$\bar{R}_m = M3(Z_m)\cdot M6(\alpha)\cdot M2(R_m)\cdot \bar{e}4, \quad (1)$$

where $\bar{R}_m$ is the radius-vector of the cutter; $Z_m = 0...H$ – the linear coordinate along the periphery of the cutting edge of the cutter, varies from 0 to the value of the tool height *H*; R_m – cutter radius; α=0...360° – angular coordinate, which specifies the cutter profile; $\bar{e}4$ – radius vector of the beginning of the coordinate system of the tool.

The nominal surface $\bar{r}_d$ of the camshaft is set by the radius vector $\bar{R}_m$ of the tool, cutter orientation relative to the coordinate system of the part and its movement relative to the shaft:

$$\bar{r}_d = M3(Z_d)\cdot M6(\theta_d)\cdot M1(X_{dm})\cdot M4(\delta)\cdot M2(Y_{dm})\cdot \bar{R}_m, \quad (2)$$

where δ is the angle of rotation of the cutter; X_{dm}, Y_{dm} – center distance of the cutter and the part in the vertical and horizontal planes, respectively; θ_d – angle of rotation of the part; Z_d – feed, describes the movement of the tool along the O_dZ_d axis relative to the part.

The feed Z_d is determined by the product of the angle of rotation θ_d of the shaft and the parameter of helical motion p:

$$Z_d = \theta_d \cdot p, \quad (3)$$

$$p = \frac{Sz}{2\cdot\pi}, \quad (4)$$

where Sz – feed per revolution of the part.

The center distance X_{dm}, Y_{dm} of the tool and the machined surface of the shaft varies during machining and depends on the angle of rotation θ_d. Therefore, the final nominal surface of the part (2), taking into account equation (1):

$$\bar{r}_d = M3(Z_d)\cdot M6(\theta_d)\cdot M2(Y_{dm}(\theta_d))\cdot M5(\delta_m)\times$$
$$\times M1(X_{dm}(\theta_d))\cdot M3(Z_m)\cdot M6(\alpha)\cdot M2(R_m)\cdot \bar{e}4. \quad (5)$$

Equation (5) is general when processing cylindrical and curved surfaces of the camshaft. Thus, when processing the curved surface of the cam, the coordinates X_{dm}, Y_{dm} change and depend on the angle of rotation θ_d of the cam. And when milling the cam section, the center of which coincides with the camshaft axis, X_{dm} does not change, and Y_{dm} is zero (Fig. 2, *a*, *b*).

To determine the profile of the machined surface of the part, the condition of contact of the cutter and shaft profiles at different points in time is used as the product of the vectors of normal $\bar{n}$ and speed $\bar{V}$ of the tool relative to the part:

$$\bar{V}\cdot\bar{n} = 0. \quad (6)$$

The normal $\bar{n}$ is determined by the product of the vectors tangent to the cutter surface. Therefore, it is necessary to differentiate the radius vector of the part $\bar{r}_k$ by two independent parameters α and j – the coordinate along the cutter profile. The relative velocity vector $\bar{V}$ is found by differentiating the radius vector $\bar{r}_k$ in the coordinate system of the part by the parameter θ_k:

$$\left(\frac{\partial\bar{r}_d}{\partial j}\times\frac{\partial\bar{r}_d}{\partial\alpha}\right)\cdot\frac{\partial\bar{r}_d}{\partial\theta_d} = 0. \quad (7)$$

Equation (7) determines the location of the contact points of the tool and part at different times.

5. Development of the general model of the milling process of camshaft support necks and cams with crossed axes of the tool and part

The contact line of the roughing and finishing plates of the cutter begins at the end of the roughing plate of the tool and ends at the periphery of its finishing plate.

To determine the contact line on the peripheral section of the cutting edge of the cutter, we perform calculations in the Mathcad software package using block (8):

$$Lk_p := \left|\begin{array}{l} \alpha \to 0, \\ for\_n \in 0....N, \\ \left|\begin{array}{l} j \leftarrow j_{\min} + \dfrac{j_{\max}-j_{\min}}{N}\cdot n, \\ \mathrm{B} \leftarrow root\left(\left(\dfrac{\partial\bar{r}_d}{\partial j}\times\dfrac{\partial\bar{r}_d}{\partial\alpha}\right)\cdot\dfrac{\partial\bar{r}_d}{\partial\theta_d},\alpha\right), \\ M^{\langle j+1\rangle} \leftarrow \left(j\right), \\ M^T, \end{array}\right. \end{array}\right. \quad (8)$$

where N is the number of segments into which the contact line at the tool's periphery is divided; $j_{\min}$, $j_{\max}$ – initial and final coordinates of the contact line on the periphery of the cutting edge of the cutter.

Determination of the contact line at the transition radius edge and the end face of the cutting edge of the cutter is carried out using a calculation unit similar to (8), only the roots of the equation are found not for the linear coordinate j, but for the angular α.

Fig. 3 shows the contact line of the cutter and the camshaft surface. The curve (Fig. 3) begins at some point j_{rk} at the end of the roughing plate of the tool, passes through the radius of its rounding (coordinate from j_{rk} to j_{r0}) and ends at the periphery of the finishing plate at the point of intersection of the cutter and part axes.

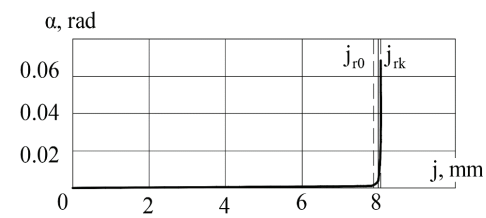

Fig. 3. Contact line of the cutter tooth and the machined surface along the tool profile

In the course of mathematical modeling of the milling process with crossed axes of the tool and part, a spatial model of the contact spot 6 (Fig. 4) of the cutting edge of the cutter 2 and the machined surface of the shaft 1 was obtained.

The contact spot 6 is formed by the intersection of the tool and part contact line 3, the line 4 of intersection of the cutter tooth and the end face of the processed surface and the line 5 of intersection of the outer surface of the workpiece and the cutter.

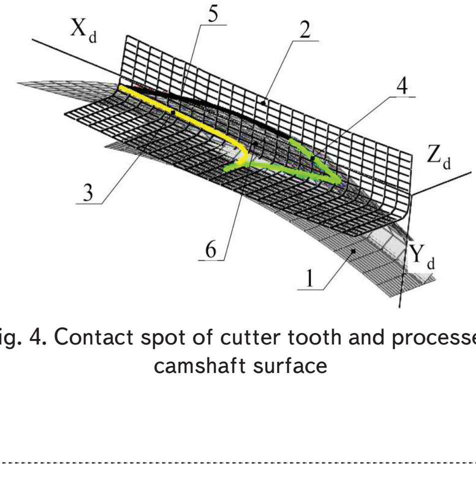

Fig. 4. Contact spot of cutter tooth and processed camshaft surface

As can be seen from Fig. 3, 4, the main allowance falls on the end face of the cutting surface of the cutter tooth, and on the periphery the allowance is minimal.

Fig. 5 shows the obtained three-dimensional model of the curved surface of the camshaft.

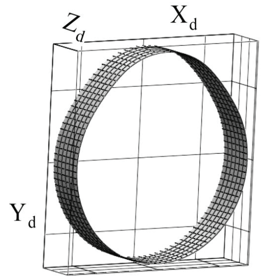

Fig. 5. Spatial model of the camshaft cam surface

The surface of the cam (Fig. 5) is formed by the movement of the contact line 3 (Fig. 4) along the equidistant to the surface of the part.

6. Investigation of the process of shaping accuracy when milling camshaft support necks and cams

The intersection of the cutter and camshaft axes forms a geometric roughness *Rz* on the treated surface (Fig. 6).

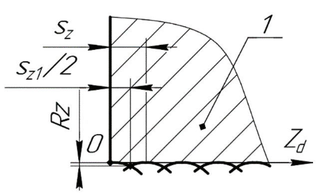

Fig. 6. Height of the microroughnesses *Rz* along the profile *Zd* of the part caused by the intersection of the tool and camshaft axes

The height of microroughnesses *Rz* (Fig. 5) is determined from (9):

$$R_z = \mathrm{Pr}_d(0) - \mathrm{Pr}_d\left(\frac{s_z}{2}\right), \tag{9}$$

where $\mathrm{Pr}_d(0)$, $\mathrm{Pr}_d(s_z/2)$ is the height of the profile of the part at the turning point of the cutter and the point which is at a distance of half the feed s_z.

In order to achieve the required roughness of the treated surface, the feed rate s_d is adjusted depending on the cutter diameter and the angle of intersection of the axes δ. In this case, to obtain high processing performance, the shaft speed is increased.

In the course of mathematical modeling of the milling process of the camshaft with crossed axes of the tool and the part, the specific productivity of milling *Q* was found, which determines the amount of metal, which is cut by the tooth area within the *j* point of its profile:

$$Q(j) = \int_{\alpha 1(j)}^{\alpha 2(j)} \left(Vn(\alpha, j) - y_v\right) \cdot \left(R_m(j) - D_m \cdot \sin\alpha_i\right) \cdot k \cdot \mathrm{d}\alpha, \tag{10}$$

where $\alpha 1(j)$, $\alpha 2(j)$ – the angles of entry and exit of the cutter tooth from the workpiece on the radius $R_m(j) - D_m \cdot \sin\alpha_i$; D_m – the linear wear of the tooth profile section in the *j*-th point; y_v – system flexibility; $R_m(j)$ – cutter radius; *k* – the coefficient that takes into account the discontinuity of the tool.

The distribution graph of specific productivity *Q* of processing (Fig. 7) when processing of a camshaft with the angle of intersection of the tool and part axes δ=1° by a cutter with a diameter of 100 mm and a height of the cutting plate of 10 mm is obtained. Starting from the point j_{r0} (coordinate of the beginning of rounding of the cutting plate of the cutter), the graph is rotated on the axis that coincides with the peripheral surface of the cutter tooth.

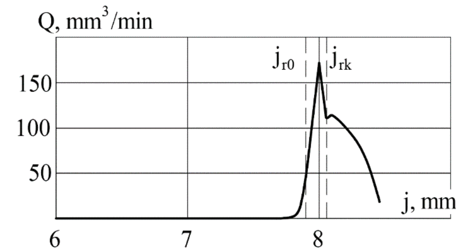

Fig. 7. Distribution of specific productivity *Q* of milling along the cutter tooth profile when processing the camshaft

The specific productivity of milling *Q* (Fig. 7) takes the largest values at the end surface of the cutter tooth (area after the coordinate j_{rk}). Therefore, the end surface is a rough area and removes the main allowance.

In the area from the coordinate j_{r0} to j_{rk}, which corresponds to the transition radius edge of the cutting plate, the specific productivity is almost evenly distributed. And takes the minimum values on the periphery of the cutting surface of the cutter (area up to the coordinate j_{r0}), which is the finishing and calibration area.

Therefore, the end of the roughing plate 3 removes the main allowance, and the unloaded periphery of the finishing plate 4 performs finishing.

This allowance distribution increases milling productivity and part shaping accuracy.

Because the end of the roughing plate has the entire allowance, it wears out faster than the finishing one.

The criterion for the transition from plastic deformation to the beginning of chip separation is the limit value of the ratio of the depth of penetration of the cutting tip into the workpiece material to the radius of curvature of its top.

When the roughing plate is triggered, its radius of curvature increases, the process of plastic deformation of the processed material begins.

Vibrations occur, the temperature in the cutting zone increases, which necessitates the replacement of the cutting blade.

In this case, the quadrilateral plate is returned to the unworn surface. This saves material, as the roughing plates wear out faster during processing, while the finishing ones remain suitable.

The specific productivity of milling for the given processing conditions on the end surface of the tooth is 90–150 mm^3/min (Fig. 7), which is 1.3–1.5 times more than when milling by existing methods.

7. Discussion of the research results of the accuracy of single-pass milling of camshafts with crossed tool and part axes

In the presented method (Fig. 1) of one-pass milling of support necks and cams of camshafts by the oriented tool, removal of the main allowance is carried out by the end face of the roughing hard-alloy plate, and finishing – the unloaded periphery of the metal ceramic finishing plate.

In this case, the angle of cutter rotation is selected from the condition of ensuring the maximum removal of the allowance with a uniform loading of its end plate. The surfaces of the camshaft are machined on the pass, which increases the accuracy of machining due to the distribution of cutting forces along the part axis and the lack of impact on its rigidity compared to the radial feed of the tool.

In contrast to the existing methods of milling camshafts [4–10], this method provides single-setup processing of support necks and cams with the same depth of cut with uneven rotation of the part. The uniformity of the depth of cut and feed along the curved profile of the cam is achieved by synchronous vertical and transverse movements of the cutter and uneven rotation of the camshaft (Fig. 2, *a*). This ensures uniform wear of the cutter's cutting inserts and increases their stability. When milling curved surfaces on CNC machines, this eliminates the impact of cutter wear on shaping accuracy and simplifies the programming of processing, as there is no need to take into account the worn profile of the tool.

Using the obtained spatial models of the tool surface (1) and part surfaces (5), a general model (8) of the process of milling the support necks and cams of the camshaft with crossed axes of the tool and part is developed. The model (8) is general for processing cylindrical and curvilinear surfaces of the camshaft, which makes it possible to analyze the processes of allowance removal and shaping any cam surface profiles (Fig. 5).

Analysis of the obtained graphs of the contact line (Fig. 3), the spatial model of the contact spot (Fig. 4) of the cutting edge of the cutter and the machined shaft surface and the specific productivity of milling Q (Fig. 7) shows that the main allowance falls on the cutting surface of the cutter tooth, and on the periphery the allowance is minimal. This distribution of allowance increases milling productivity and part shaping accuracy. The finishing plate, which has small allowance values, provides low geometric surface roughness, and the roughing plate provides high processing productivity (90–150 mm^3/min).

With this method of milling, the end of the roughing plate has the main allowance, it wears out faster than the finishing one. Therefore, the ability to replace only the worn roughing plate saves material of the finishing one.

The intersection of the cutter and camshaft causes geometric roughness Rz on the treated surface (Fig. 6). Therefore, to obtain its required value, the feed s_d is adjusted depending on the cutter diameter and intersection angle of the axes. To ensure high processing productivity, the shaft speed is increased.

Since the tool is fed to the entire depth of cut due to the presence of grooves between the support necks and cams, this method imposes restrictions: the height of the cutter is limited by the width of the camshaft groove. The three-dimensional model of the process of milling the support necks and cams of the camshaft with an oriented tool makes it possible to obtain only the geometric profile of the part. This takes into account the influence of the cutter profile, depth of cut and feed without the rigidity of the system and vibrations.

In the future, the proposed method can be applied to milling processes of various cylindrical surfaces of complex profile with crossed axes of the tool and part.

8. Conclusions

1. Spatial geometric models of the tool surface and the curved surface of the part are developed, which make it possible to set any profiles depending on the tool and part parameters, as well as to analyze the processes of allowance removal and shaping during milling of camshaft support necks and cams.

2. On the basis of the developed models, the method of one-pass milling of cylindrical and curvilinear surfaces of camshafts at a single setup is investigated. At the same time, rough milling is carried out by the end face of a four-sided rough hard-alloy plate, and finishing – by the unloaded periphery of the metal ceramic finishing plate. Passage processing increases shaping accuracy, because the cutting forces are directed along the axes of the treated surfaces. In the process of milling the curved surfaces of the cams, the tangent to the curved surface of the cam is located vertically. This eliminates additional deformations and stresses due to the simultaneous vertical and transverse movements of the cutter. Also the influence of the tool radius and wear on shaping accuracy of the processed surfaces of camshafts, which simplifies programming of processing is excluded.

3. Researches of the accuracy of surface shaping by the proposed method show that different allowances along the end face of the roughing and the periphery of the finishing plates of the cutter increases productivity (90–150 mm^3/min) and processing accuracy (IT 7–8). And the ability to rotate only the roughing plate, when it wears, saves material of the finishing one and reduces the cost of processing. The proposed method of single-pass milling of support necks and cams of camshafts can be used in the processing of various surfaces of rotation of complex profile with crossed axes of the tool and part.

References

1. Shkarlet, S., Kholiavko, N., Dubyna, M. (2019). Information economy: management of educational, innovation, and research determinants. Marketing and Management of Innovations, 3, 126–141. doi: https://doi.org/10.21272/mmi.2019.3-10
2. Brecher, C., Wellmann, F., Epple, A. (2017). Quality-predictive CAM Simulation for NC Milling. Procedia Manufacturing, 11, 1519–1527. doi: https://doi.org/10.1016/j.promfg.2017.07.284
3. Nguyen, V. (2018). Design and manufacturing camshaft using on hybrid vehicles. International Journal of Mechanical Engineering and Technology (IJMET), 9 (6), 277–284. Available at: http://www.iaeme.com/MasterAdmin/Journal_uploads/IJMET/VOLUME_9_ISSUE_6/IJMET_09_06_032.pdf

4. Shlifoval'nye stanki zavod «Harverst». Har'kovskiy stankostroitel'niy zavod «Harverst». Available at: http://harverst.com.ua/upload/files/Buklet_stanko_ru.pdf
5. Li, J., Zhang, W., Shen, N. Y., Wang, X. L. (2013). A Novel Method for Kinematic Optimization of Camshaft Non-Circular Grinding. Advanced Materials Research, 690-693, 3253–3257. doi: https://doi.org/10.4028/www.scientific.net/amr.690-693.3253
6. Deng, Z. H., Wang, J., Cao, D. F., Liu, W., Wang, L. L. (2009). Research on Dynamic Optimization and Simulation of Camshaft Grinding Process. Advanced Materials Research, 69-70, 44–48. doi: https://doi.org/10.4028/www.scientific.net/amr.69-70.44
7. Chen, G., Mei, X., Zheng, T. (2009). Research on the key technologies of CNC noncircular camshaft grinding. 2009 International Conference on Mechatronics and Automation. doi: https://doi.org/10.1109/icma.2009.5244827
8. JUCAM – Cam grinding. Junker. Available at: https://pdf.directindustry.com/pdf/erwin-junker-maschinenfabrik-gmbh/jucam-cam-grinding/9216-323555.html
9. JUCRANK. Crankshaft grinding. JUNKER. Available at: https://www.junker-group.com/fileadmin/user_upload/Prospekte/JUNKER_JUCRANK_en.pdf
10. Flexible manufacturing systems (2015). Heller.
11. Kalchenko, V., Sira, N., Kalchenko, D., Aksonova, O. (2018). Investigation of the milling cylindrical surfaces process with tool and shaft crossed axes. Technical sciences and technologies, 4 (14), 18–27. doi: https://doi.org/10.25140/2411-5363-2018-4(14)-18-27
12. Sliednikova, O., Vynnyk, V., Sklyar, V., Aksonova, O. (2019). Modular 3d modeling of tools, process of adaptation removal and forming at milling the cams with crossing tools and details. Technical sciences and technologies, 1 (15), 53–62. doi: https://doi.org/10.25140/2411-5363-2019-1(15)-53-62