Technological Assurance of Machining Accuracy of Crankshaft

Alexey Kotliar, Yevheniia Basova(✉), Maryna Ivanova(✉),
Magomediemin Gasanov, and Ivan Sazhniev

National Technical University “Kharkiv Polytechnic Institute”,
Kharkiv, Ukraine
e.v.basova.khpi@gmail.com, ivanovamarynal@gmail.com

Abstract. The typical technological processes of manufacturing crankshafts are considered. The main directions for technological assurance of the accuracy and quality of machining these parts are given. For a compensation of an influence of cutting force on a quality and an accuracy of manufacturing crankshafts, the design of the following steady rest was proposed. The studies of a dependence of the total cutting force for grinding wheels with different grit from ultimate strength of the material, width of main journal and infeed speed were made. The design calculations of the spring were performed and the value of the pressing force developed by spring was obtained, which is capable to level the influence of the cutting force on the deformation processes during crankshaft machining. The elastic deformations which occur when grinding the crankshaft main journal with and without the proposed steady rest were estimated by simulation modeling with finite elements method. The values of pressing forces, which are necessary to compensate the influence of the total cutting force on the shape accuracy of shaft, were obtained.

Keywords: Crankshaft · Main journals · Following steady rest · Variable rigidity · Cutting forces

1 Introduction

Modern mechanical engineering is characterized by the intensification of technological processes for manufacturing of critical parts of machines, to the quality of which the high requirements are made.

It is known that crankshaft constructively and technologically is complex part. Moreover it are considered ones of the most critical and stressful part of internal combustion engine, as it affects on reliability of the assembly and of its structure in whole. The operating conditions of the crankshafts and associated with them parts require precise dimensions and the correct relative positions of the individual elements.

From the analysis of the manufacturing techniques of such parts, it was established that crankshafts are made from carbon, chromium-manganese, chromium-nickel-molybdenum steels, and also from special high-strength cast irons. Workpieces for medium-sized steel crankshaft are made by forging in closed dies on hammers or presses. It is worth noting that due to the high requirements to mechanical strength of

M. Diering et al. (Eds.): *Advances in Manufacturing II* - Volume 5, LNME, pp. 37–51, 2019.
https://doi.org/10.1007/978-3-030-18682-1_4

the crankshaft, a fibers arrangement of the workpiece material has a great importance in order to avoid their cutting during subsequent machining. In addition, the complexity of the geometrical and constructional forms of the crankshaft, its lack of rigidity, high requirements to an accuracy of machining surfaces cause special demands of choice of workpiece locating methods, fixturing methods and processing methods, as well as the sequence and combination of operations and the choice of metal-cutting equipment, machining attachments and tooling. In this case, the main bases of the crankshaft, as a rule, are the bearing surfaces of the main journals. In some cases, surfaces of the center holes are chosen as technological bases. In some operations, when processing the crankshaft in the centers due to its relatively low stiffness, the outer surfaces of the pre-treated necks are used as additional technological bases. Main journals, which are later used as technological bases for machining of crankpins and other surfaces, can be operated on conventional lathes. However, since the crankshaft is not enough rigid part and it tends to bend and twist under the action of cutting forces during processing, especially when one-sidedly drive lathes, specialized machine tools are used to process the main journals of the multithrow crankshaft. The peculiarity of such equipment is in the presence of a central or two-way drive, whose task is to reduce bending and twisting moments. To simplify the designs of such machine tools or utilize standard equipment, various kinds of devices and steady rests are used to eliminate significant bends and twisting of crankshafts. Their task is to eliminate the elastic deformations caused by cutting forces, taking into account the low and variable rigidity of the part.

From the analysis of existing structures such devices, it was found that the task of developing following steady rest for efficiently machining parts with variable rigidity, which depends on its angle of rotation, is promising.

2 Literature Review

From the analysis of recent researches it has been established that much attention is paid to the issues of ensuring the qualitative characteristics of the crankshaft and its further reliable utilizing [1–10].

For example, the authors of work [2] have presented a study by static simulation of a crankshaft and a single cylinder 4-stroke diesel engine. The analysis was accomplished for finding critical location in crankshaft.

Authors of research [3] have conducted a dynamic simulation on a crankshaft for a single cylinder four stroke camless Engine. Finite element analysis was performed in research to obtain the variation of stress magnitude at critical locations. The analysis was done for different engine speeds and as a result critical engine speed and critical region on the crankshaft were obtained.

But it is worth mentioning that works [1–5] were based on the fact that the crankshaft has ideal operating characteristics.

Author of paper [6], taking into account the qualitative characteristics of the crankshaft, have presented the results of the analysis of how sea waves affect the angular speed of a propulsion. In the article, the method of assessing the state of the ship’s engine was considered. Implementation of the method is possible, including with the appropriate qualitative characteristics of the crankshaft.

In article [7] describes the details of the method designed to determine parameters of vehicle's internal combustion engine with compression ignition during road tests. The method requires simultaneous measurements for the crankshaft rotation frequency, fuel pressure in the injector, pressure in the combustion chamber, air pressure and temperature in the intake system [7]. It is not possible to obtain an adequate mathematical model using this method if the crankshaft does not meet the criteria for quality and accuracy.

In the article [8] authors have considered the crankshaft (taking into account the fact that the part corresponds to high quality and accuracy characteristics) and presented the model of the crankshaft taking into account the coupling of bending and torsional vibrations. This allowed the authors present two approaches to modeling torsional and bending vibrations in crank systems and indicate the application area of the proposed methodology.

In addition, it is worth to notice that an assurance of production productivity of crankshafts is also of interest [11, 12]. This requires a search for new technological solutions to optimize the manufacturing process of such parts [13–15].

Authors of paper [16] have attempted to focus on to study the various methods preferred for designing and optimizing the crankshaft for safer working under various boundary conditions by various researchers.

However, it should be remembered that the technology of machining the crankshaft is a complex task, the solution of which requires taking into account of its design complexity and low rigidity, the presence of significant and not uniform deformation under the action of cutting forces and, at the same time, the need to ensure the required accuracy.

Development and application of various auxiliary devices for complex parts manufacturing allow obtaining the required quality characteristics of the products [17–20].

The flexible fixture characterized by high level of flexibility was proposed for CNC multiaxis machining operation [21]. Experimental research of it is presented in paper [22], which provides sufficient accessibility and allows to perform multiaxis machining of parts.

However, current works aimed at optimizing the technological process of manufacturing a crankshaft on grinding operations by the development of auxiliary following compensating devices could weren't found.

3 Research Methodology

3.1 Mathematical Substantiation of the Mechanical Component of the Design of the Following Steady Rest

A decision to develop an intermediate following support for grinding especially the middle part of the crankshaft was made. The purpose of the support is to be able to compensate for the lack of rigidity along the length of the shaft and uneven rotation angle.

It should be noted that the development of a following steady rest for the efficient processing of crankshafts requires an analysis of technological conditions when the detail is been manufacturing. From the point of view of the analysis of the technological process of crankshafts manufacturing, it is known that grinding operations of main and crankpin journals are the most responsible operations for manufacturing such parts. When performing these operations under the action of cutting forces, elastic deformations of the elements of the technological system and mainly workpiece are occurred, which lead to the appearance of form errors of the processed crankshaft's journals. It follows from this that the most important parameters to ensure the accuracy and quality of crankshafts are the machining conditions and cutting forces those influence on the part during the manufacturing process.

Estimation of the value of the tangential component of the cutting force P_z for cylindrical plunge grinding is possible by the formula (1). This formula is based on experimental studies of mentioned process, performed by professor Stepanov M.S. and Khodakov L.V. in the machine tool laboratory of the Kharkiv machine-tool building plant [23].

$$\mathrm{P}_z = 2,254\frac{\sigma_t^{0,342}\cdot H^{0,258}\cdot V_p^{0,945}}{z^{0.051}\cdot S_p^{0.073}\cdot S_{axial}^{0.073}\cdot t_{axial}^{0.026}}\cdot B, [N] \tag{1}$$

where σ_t – the ultimate strength of the workpiece material at high temperatures (600 °C), kgf/mm^2; H – sonic index of grinding wheel; z – grit of grinding wheel; V_p – infeed speed, mm/min; S_p – peripheral speed of workpiece rotation, m/min; S_{axial} – longitudinal speed of grinding wheel dressing, mm/min; t_{axial} – dressing depth, mm; B – grinding width, mm.

In the work [23] the researchers noted that the radial component P_y of the cutting force when peripheral speed of workpiece rotation is in a range 30 … 70 m/min is in 2.2 times bigger than P_z.

Then the total cutting force can be determined by the formula (2):

$$P = \sqrt{P_z^2 + P_y^2} = \sqrt{P_z^2 + (2.2\cdot P_z)^2} \approx 2.417\cdot P_z, [N] \tag{2}$$

Presumably this total cutting force can cause an elastic deflection of a part and further loss of quality.

3.2 Mathematical Substantiation of the Elements of the Following Steady Rest for Compensation of an Elastic Deflection

For a compensation of an influence of cutting force on a quality and an accuracy of manufacturing crankshafts, the design of the following steady rest was proposed [24]. One of the main and distinguishing features of the proposed device is a profile cam (Fig. 1). The geometrical profile of the cam is determined from a polar diagram of the deformation of cross-section of a main journal of crankshaft, depending on the applied total cutting force when grinding [24] (Fig. 2).

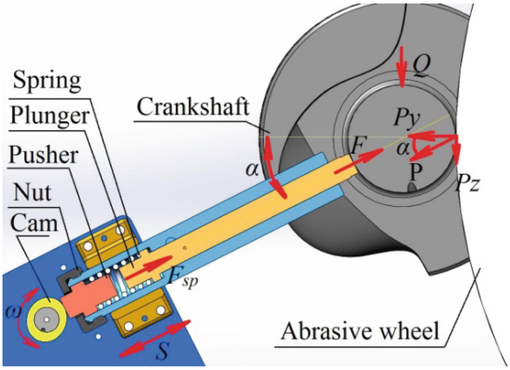
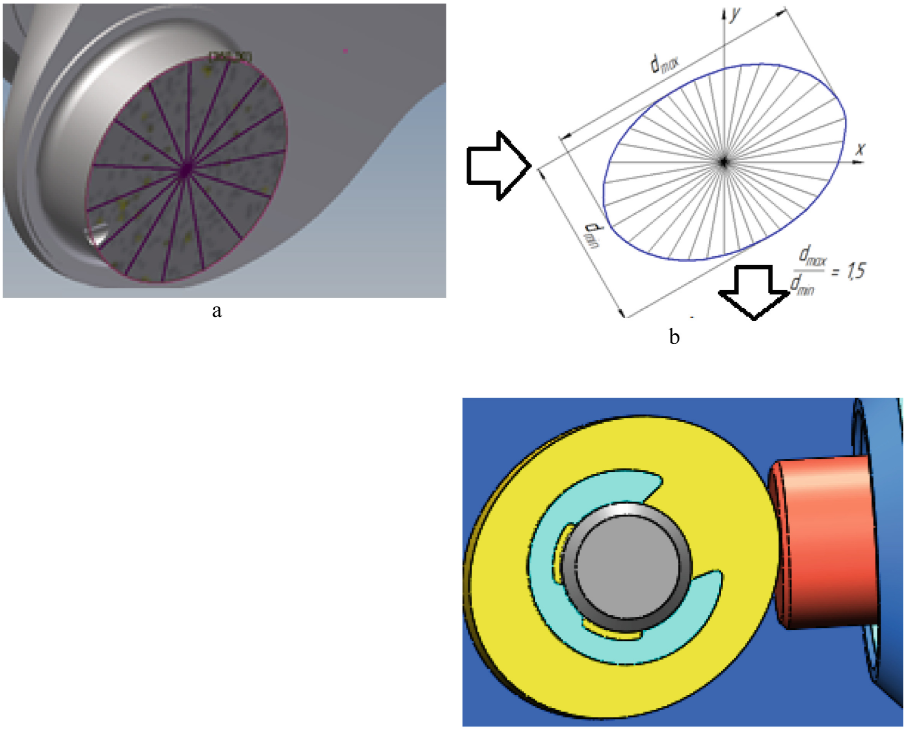


Fig. 1. Scheme of the work of the following steady rest when grinding main journal of crankshaft: P_y, P_z – cutting force components; P - total cutting force; Q - crankshaft weight; F - balancing force; S - plunger movement; F_{sp} – initial spring strain force; ω - angular speed of the cam rotation; α – angle between the closing cutting force P and the horizontal plane.



a

b

c

Fig. 2. A principle of the profile cam plotting: a – main journal cross-section; b – a polar diagram of the deformation of a cross-section of a crankshaft main journal; c – a profile cam included in the following steady rest construction.

The cam is actuated by electric motor and rotates moving the pusher, which moves the plunger with a carbide plate through the spring (See Fig. 1). The plunger applies a compensation force F to the crankshaft journal, thereby reducing its elastic deflection. A return of the plunger to its original position, as well as the constant contact of the pusher with the cam is provided by a spring. Spring stiffness and initial pressing force are adjusted by nut. An essential condition for the effective work of the steady rest is the determination of the initial position of the cam relative to the main journal and their subsequent synchronous rotation with the same rotation speed.

The angle between the total cutting force P and the horizontal plane α can be determined from the formula (3)

$$\alpha = \arctan \frac{P_z}{P_y} \tag{3}$$

An important element of the device design to ensure its adequate work is a spring. Therefore, an important stage in the design of the following steady rest is determination of the geometric dimensions and stiffness of the spring.

The pressing force of spring when deformation is maximal can be determined from the formula (4):

$$F_3 = \frac{F_2}{(1 - \delta)} \tag{4}$$

where F_2 – pressing force of spring when working deformation; δ – relative inertia clearance.

Then the critical speed V_c of the spring movement is determined by the formula (5)

$$V_c = \frac{\tau_3 \cdot \left(1 - \frac{F_2}{F_3}\right)}{\sqrt{2 \cdot G \cdot \rho \cdot 10^{-3}}} \tag{5}$$

where τ_3 – maximum tangential stress of spring; G – shear modulus; ρ – dynamic density of material.

The design of the steady rest can be considered reliable if condition of safe operation during $1 \cdot 10^4$ h is fulfill (6):

$$\frac{V_{\max}}{V_c} < 1 \tag{6}$$

where $V_{\max}$ – maximum moving speed of the moveable spring end.

Fulfillment of condition (6) allows calculating the spring stiffness (7), determining the number of its coils (8) and the average diameter (9):

$$c = \frac{F_2 - F_1}{h} \tag{7}$$

$$n_1 = \frac{c_1}{c} + n_2 \tag{8}$$

$$D = D_1 + 2d \tag{9}$$

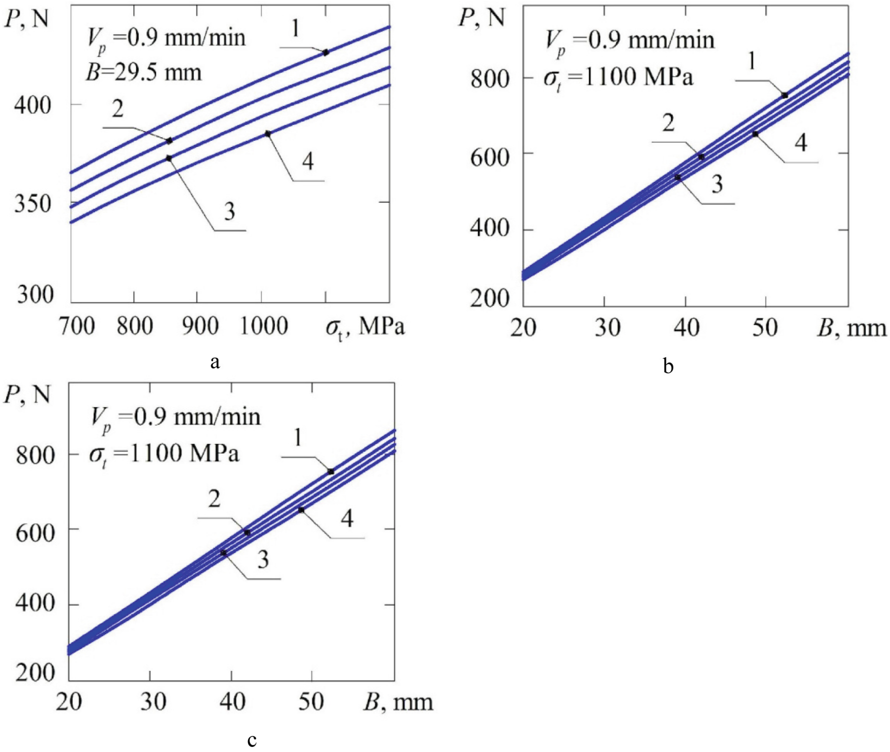
where h – a spring stroke; F_1 – a pre-strain force, n_2 – the number of bearing coils that equals 1,5, c_1 – a stiffness of one coil, d – a wire diameter, D_1 – a spring inside diameter.

The design parameters of the spring can be optimized based on the results of computer simulation by the finite element method.

4 Results

To check the efficiency of the proposed steady rest construction the crankshaft grinding process was simulate with next parameters: a main journal diameter $d_{\mathrm{mj}} = 53$ mm; rotation rate of crankshaft $n_{\mathrm{cr}} = 90$ rev/min; infeed speed $V_{\mathrm{P}} = 0.9$ mm/min; width of main journal $B = 29.5$ mm; wheel speed $V_{\mathrm{w}} = 50$ m/sec. According to formula (2) total cutting force 367 N.

The studies of a dependence of the total cutting force for grinding wheels with different grit (*1* – z = 10 µm; *2* – z = 16 µm; *3* – z = 25 µm; *4* – z = 40 µm) at temperature T = 600 °C from ultimate strength of the material (Fig. 3a), width of main journal (Fig. 3b) and infeed speed (Fig. 3c) were made.



a

b

c

Fig. 3. A dependence of the total cutting force from: a – ultimate strength of the material; b – width of main journal; c – infeed speed.

From the Fig. 3 it can be seen that value of the total cutting force increases in direct proportion to an increase in an infeed speed and a width of the main journal. A rising of a ultimate strength of a material also results in an increase of a cutting force, however an increasing of the grit of grinding wheel the cutting force decreases insignificantly.

Knowing the values of the total cutting force occuring during infeed grinding, the design calculations of the spring (Table 1) were performed and the value of the pressing force developed by spring was obtained, which is capable to level the influence of the cutting force on the deformation processes during crankshaft machining.

To estimate the elastic deformations which occur when grinding the crankshaft main journal with and without the proposed steady rest a simulation modeling was performed. This made it possible to establish the maximum displacements of the processed journal in accordance with its circular diagram along the X, Y axes and at the expected point of contact with the steady rest (Figs. 4 and 5), and to determine the maximum displacements on the crankshaft as a whole (Tables 2 and 3).

As can be seen from Fig. 5 the polar diagram of deformations of the crankshaft main journal has eccentricity along the axes X and Y (See Fig. 5a, b), but at the point of the supposed contact of the main journal and steady rest the polar diagram of deformations has the desired shape (See Fig. 6). In addition, the simulation results showed that the smallest elastic deformations of the crankshaft are observed when the angle between the directions of the total cutting force and the pressing force of the steady rest is equal 156º.

Knowing the values of crankshaft main journal displacements and geometrical parameters of the spring, the pressing forces, which are necessary to compensate the influence of the total cutting force on the shape accuracy of shaft, were obtained (Table 3).

Table 1. The geometrical parameters of the working spring of the following steady rest.

Name of parameter	Description	Value
Pressing force of spring when maximum deformation, N	F_3	680
Wire diameter, mm	d	5
Stiffness of one coil, N/mm	C_1	310
Spring stiffness, N/mm	C	40
Number of coils	n_1	10
Spring inside diameter, mm	D_1	32
Maximum deformation, mm	S_3	17
Length in free condition, mm	l_0	67

An example of the results of modeling the loading by forces (total force and pressure force) of the crankshaft main journal by the finite elements method is shown on the Fig. 7. In addition, the figure clearly shows the points of contact between the steady rest and the grinding wheel with the workpiece. In addition, the points of contact between the steady rest and the grinding wheel with the workpiece are clearly indicated in the figure. This, in turn, allows us to estimate the distribution of elastic deformations

Table 2. Investigation of deformation processes when grinding of crankshaft main journal is without using following steady rest.

Angle of crankshaft rotation, [º]	Maximum displacement of the main journal along the axis X, [μm]	Maximum displacement of the main journal along the axis Y, [μm]	Maximum displacement of the main journal at an expected point of contact, [μm]	Maximum displacement of the crankshaft, [μm]
0	2,28	2,3	2,12	3
24	2,26	2,47	2,34	3,3
48	2,24	2,4	2,21	3,2
72	2,15	2,2	2,08	2,9
96	1,96	2,05	1,9	3,2
120	2,04	1,78	1,85	2,3
144	2,15	1,72	1,9	2,6
168	2,3	1,8	2,08	3
192	2,4	1,9	2,2	3,3
216	2,42	1,94	2,2	3,3
240	2,4	1,92	2,11	3,1
264	2,26	1,86	1,97	2,4
288	2,03	1,85	1,82	2,2
312	2,02	1,96	1,86	2,4
336	2,1	2,18	1,97	2,8

(displacements) of the crankshaft during machining. As the results of computer simulation showed, the maximum elastic deformations are observed when the cam is rotated on an angle of 192º and equals $0.69 \cdot 10^{-3}$ mm for the processed journal and $0.7 \cdot 10^{-3}$ mm – for crankshaft.

When comparing the data obtained from the simulation of machining with and without using of the following steady rest, it was established that its application makes it possible to reduce elastic deformations by an average of 87% (Figs. 8 and 9).

This allows saying about positive trend to reduce the negative effects of cutting force on crankshaft main journal by application the proposed following steady rest. However, it was found that theoretical calculations of the required spring stiffness have an error (Fig. 8). And to result in the value of main journal deformation to 0, it is necessary to perform an experimental optimization of the spring parameters.

Thus it can be mentioned that the proposed design of following steady rest is relevant and operative for improving the quality and accuracy of machining the crankshaft, as well as reducing the manufacture time due to the possibility to intensify of cutting conditions without the threat of increase of deformations and shape errors.

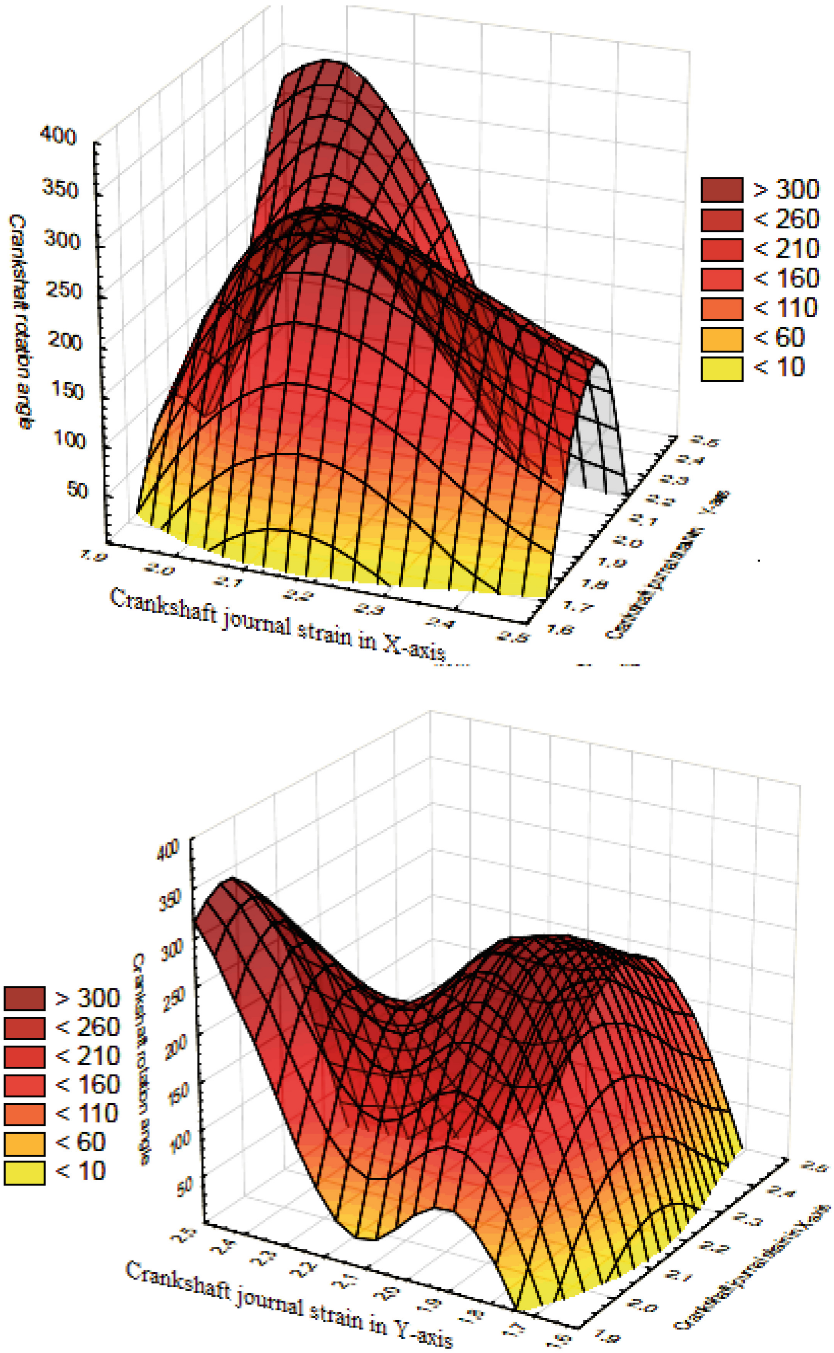


Fig. 4. The tension distribution of processed crankshaft main journal in X and Y axes.

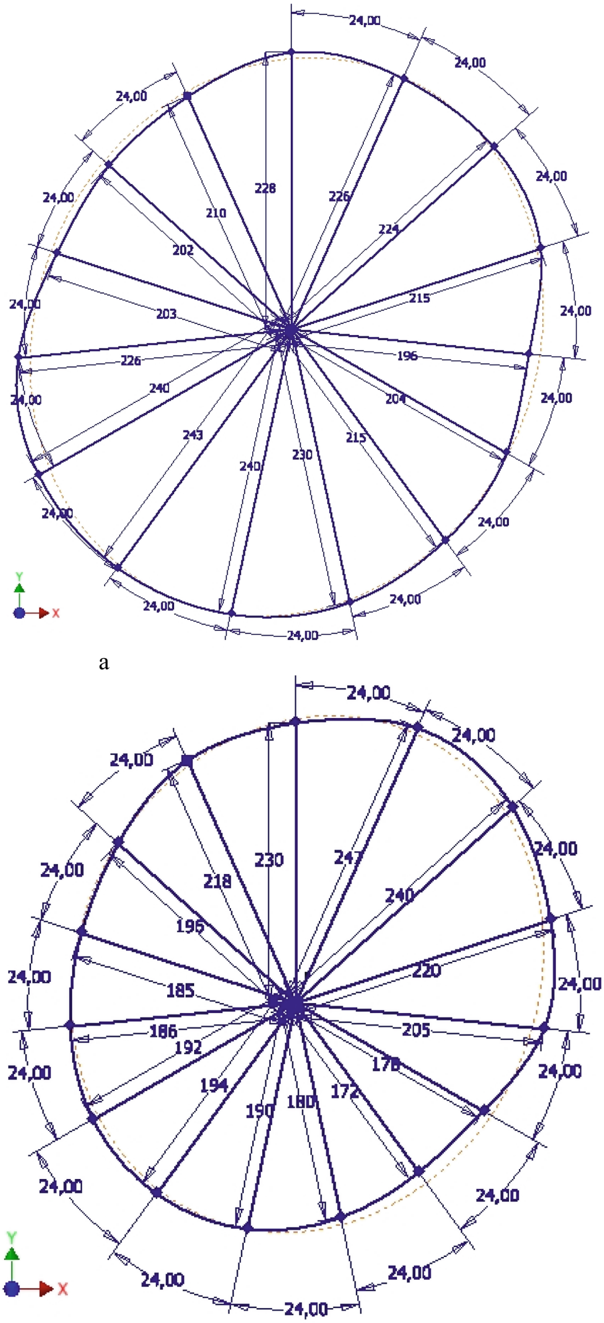


Fig. 5. The polar diagrams of elastic deformations of the crankshaft main journal which are got from simulation results: a – displacements in X-direction; b – displacements in Y-direction.

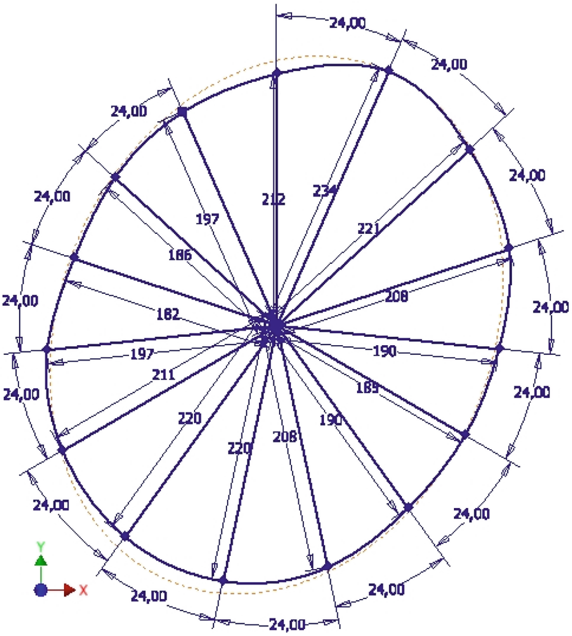


Fig. 6. The polar diagram of elastic deformations of the crankshaft main journal which are got from simulation results. Displacements at the contact point of the main journal and steady rest.

Table 3. Investigation of deformation processes when grinding of crankshaft main journal is with using following steady rest.

Angle of crankshaft rotation, [°]	Spring pressing force, [N]	Maximum displacement of the main journal along the axis X, [µm]	Maximum displacement of the main journal along the axis Y, [µm]	Maximum displacement of the main journal at the point of contact, [µm]	Maximum displacement of the crankshaft, [µm]
0	445	0,15	0,45	0,52	0,52
24	471	0,2	0,45	0,68	0,68
48	445	0,12	0,3	0,54	0,54
72	419	0,12	0,17	0,37	0,45
96	393	0,21	0,09	0,21	0,5
120	393	0,21	0,09	0,29	0,54
144	419	0,12	0,17	0,38	0,54
168	445	0,16	0,27	0,53	0,55
192	471	0,3	0,38	0,69	0,7
216	445	0,2	0,24	0,53	0,54
240	419	0,16	0,10	0,37	0,38
264	393	0,24	0,05	0,21	0,47
288	367	0,3	0,15	0,15	0,55
312	393	0,23	0,07	0,24	0,53
336	419	0,1	0,13	0,39	0,5

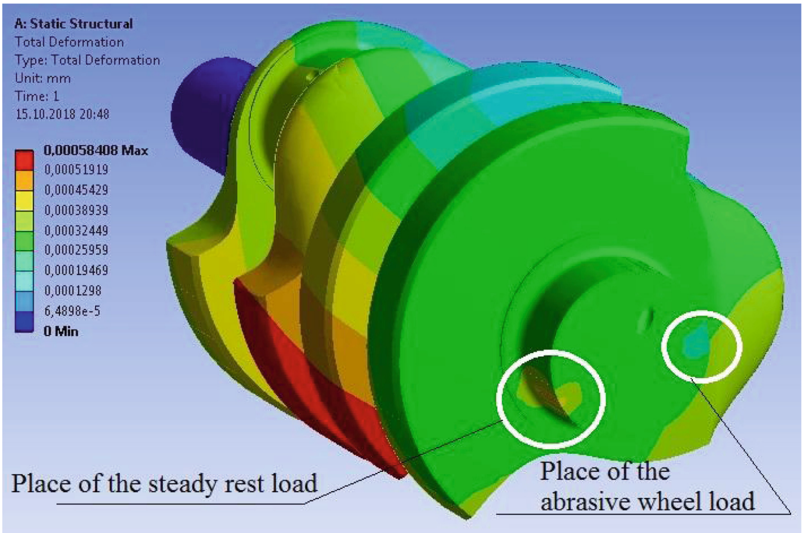


Fig. 7. Investigation of the crankshaft deformations under the influence of the forces from the steady rest and the grinding wheel

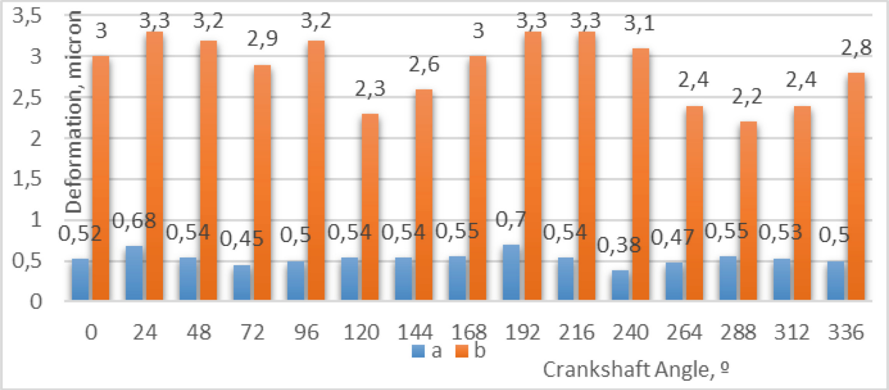


Fig. 8. Comparative analysis of the maximum deformations of the crankshaft depends on an angle of cam rotation: a – with steady rest, b – without steady rest

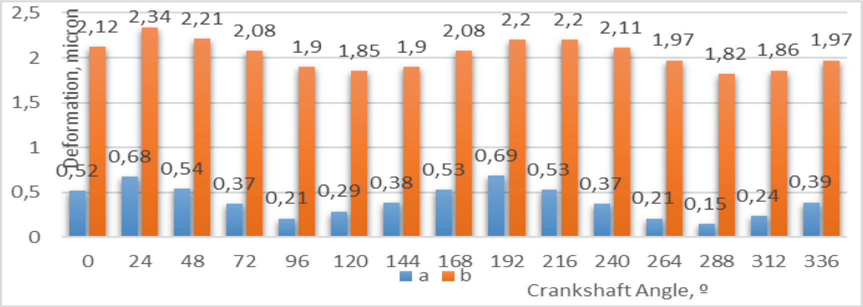


Fig. 9. Comparative analysis of the deformations of the main journal depends on an angle of cam rotation: a – with steady rest, b – without steady rest

5 Conclusions

Using of the following steady rest for machining the main journals of crankshaft allows compensating the influence of cutting forces and minimizing the deformation component of the grinding process. This will permit to stabilize the thickness of cut by ensuring the constancy of the infeed cycle and will result in a reduction of roughness and an increase of shape accuracy of the machined main journal.

The using of the steady rest may increase the crankshaft machining productivity due to the intensification of cutting conditions without the threat of appearance of deformations and shape errors of the processed journals.

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