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Impact of Technological System's Characteristics on the Machining Accuracy of Bearing Rings

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Abstract. The article shows the influence of the technological system of an automated lathe, in particular cam chucks, on the accuracy of machining bearing rings for production conditions. The value of the deformation during machining, i.e., the non-circularity of the ring of a single row tapered roller bearing 32017X in outer diameter, was investigated. For the study, samples were selected that were processed under the same conditions directly in the production unit of PJSC "SKF Ukraine" without interference with the technological process. The use of replaceable floating cams in the chuck design was proposed to increase the accuracy and productivity of machining. Experimental studies have shown that the machined surface's ovality depends on the chuck cams' clamping force. The effectiveness of computer processing of statistical data on the accuracy control of engineering products was shown. Implementing machining accuracy control in production using the Minitab computer program was presented. It was proven that the quality of products is formed under the influence of the use of modern computer technologies at all stages of manufacturing and control of parts, which ensures research in a wide range of changes in technological parameters and comparison of individual studies with actual machining conditions on the machine, with the results of a sufficient level of reliability.

Keywords: turning, machining errors, production, workpiece, cam chuck, product innovation.

1 Introduction

In modern mechanical engineering, the requirements for improving machining accuracy are constantly growing, and the problems of achieving accuracy are characterized by extreme multifactorial. A number of factors practically do not change in the process of processing: deformation of the workpiece and elements of the technological system under the influence of fastening forces; errors of the base surfaces of the workpiece and its installation on the machine; errors in the manufacture and installation of the tool; geometric errors of the machine. Other factors change significantly in the processing under the influence of variable forces, variable stiffness, changes in temperature conditions, and parameters of cutting and friction processes [1, 2].

Machining of bearing rings on turning operations is associated with the deflection of machined surfaces under the cutting and fixing forces with the subsequent formation of related processing errors. During the clamping of thin-walled rings in the chucks, the deformation of the workpiece is formed, which depends, in particular, on the number of points of application of force and the magnitude of the clamping force. The part is compressed, and at the points of mechanical contact in the material, there are increased stresses caused solely by changes in the wall thickness of the workpiece. This leads to a processing error of the ring - non-roundness. The roundness of the rings affects the performance. In particular, it reduces the durability of rolling bearings several times [3]. The magnitude of this error depends on the number of cams and the extent to which the shape of their clamping surface approaches the shape of the part.

The more cams and their clamping surface corresponds to the shape of the part, the smaller the error will be.

Moreover, even with perfectly correct machining, the part after removing from the machine, as a result of relaxation of stresses in the metal, acquires a cut (partial case of non-roundness) with the number of faces by the number of cams. To reduce it, choosing a suitable scheme of installation and fastening of workpieces is necessary, which primarily ensures the accuracy of the final processing of parts and increases the productivity of metalworking [4]. In these conditions, the problem of identifying reserves to improve the accuracy of machined surfaces is actual, in particular, the rings of roller bearings during their manufacture in automated production.

The study aims to ensure the accuracy of turning bearing rings due to the selection of the optimal cartridge design for production conditions.

2 Literature Review

A review of literature sources is engaged in researching and describing this problem [5, 6]. Their works are devoted to research on analytical calculations of machining error, ensuring the accuracy of cutting parts, improving the accuracy of machines, developing and testing clamping structures, and their drives for fixing and processing non-rigid parts. However, at the same time, it is essential to study the accuracy of operations for the conditions of a particular production. Machining of products with a given accuracy and surface quality depends not only on the machine tool but also on the entire technological processing system (TPS). The tool, workpiece, chuck, and cutting modes are included in the TPS [7]. For the most part, errors due to deformations of the TPS make up a significant part of the overall machining error. In particular, it is advisable to consider in more parts the error due to the clamping force of the workpiece. These forces cause elastic deformations of the workpieces, which generates errors in the shape of the processed workpieces.

Large deformations can occur when clamping thin-walled, non-rigid workpieces such as rolling bearing rings. Non-roundness rings can reduce the service life of rolling bearings by several times. To reduce the error, choosing the correct installation and clamping scheme for the workpieces is necessary. The amount of error also depends on the number of cams and how close the shape of their clamping surface is to the shape. The above allows us to conclude that roughing and finishing machining should be performed for precision parts. Furthermore, take measures to reduce the machining error, which is essential for finishing operations and roughing.

One of these factors in improving the quality of parts is the timely elimination of errors during machining. This problem can be solved by identifying reserves for improving the accuracy of machined surfaces. This can be done by introducing analytical processing with the help of quality management software, detection, and avoiding errors in manufacturing various products.

In [8], a dynamic model of a flexible rotor supported by ball bearings with rubber damping rings was proposed by combining the finite element and the mass-centralized method. In the proposed model, the rotor was built with the Timoshenko beam element, while the supports and bearing outer rings were modeled by the mass-centralized method.

To verify the correctness of the modeling method [9, 10], theoretical and experimental analysis is carried out by a rotor-bearing test platform, where the error rate between the theoretical and experimental studies is less than 10 %. Besides that, the influence of the rubber damping ring on the dynamic properties of the rotor-bearing coupling system was also analyzed.

This paper [11] presents a practical approach for failure mode prediction using multiple sensors installed in a bearing ring grinder for process control and condition monitoring.

A number of researchers have studied the design of clamping chucks for fixing and machining non-rigid parts [12, 13]. It has been established that all clamping chucks for fixing such parts are made with clamping elements made precisely to the diameter of the clamp and have systems for distributing forces between the cams. When choosing any design of a clamping chuck, it is necessary to solve the problem of finding the distributed loads in its elements. In addition, it is also necessary to know the displacement values of individual points of the selected design, both under static external loads and under variable loads.

The process of mechanical processing of bearing rings creates a surface layer of plastically deformed material, which acts as a source of residual stresses in the cross-section of the workpiece. These stresses significantly impact the physical, mechanical, and chemical properties of the surface layer of the workpiece. During mechanical processing, plastically deformed material from the previous stages of production is removed, which causes deformation of the blank of the bearing rings. At the next stages of production, residual stresses and shape deviations during mechanical processing can affect the deformation of the workpiece.

In addition, clamping forces lead to elastic deformation of the ring. In the case of a 3-jaw cartridge, the triangle occurs after unzipping. Basically, these shape deviations depend on the clamping forces and the number of cams [8, 9]. Elastic deformations due to chuck clamping affect the stability of processing [10-12].

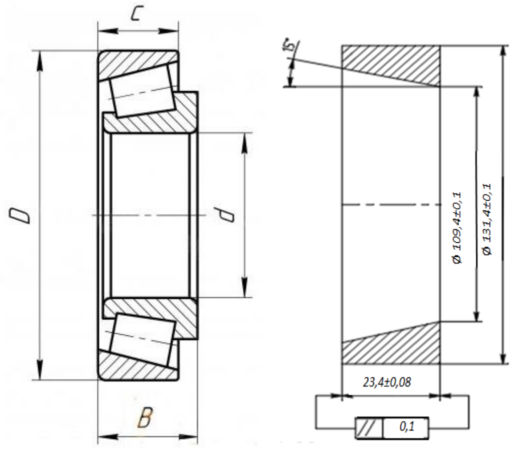
The structure of the pattern recognition process will be introduced, this includes the signal pre-processing, the selection of the most suitable features for this specific application using Minitab [13].

In particular, the determination of deformations of the part in the process of roughing and the definition of indicators that reduce the impact of the error of deformation of the workpiece on the accuracy of processing.

3 Research Methodology

For bearing rings, high requirements are set for the geometric shape after turning. Parameters such as the inconsistency of the inner diameter of the ring, the angle of the inner diameter, the inconsistency of the outer diameter and its conicity, the inconsistency of the width of the ring, as well as deviations from the roundness of the shape (the ring cut) are controlled. When the thin-walled ring is fixed in the cartridge, its elastic deformation occurs, which causes a form error in the processing process, both in roughing and finishing operations. The part will examine the technological heredity, and the geometric shape in cross-sections obtained after the processing stage. Therefore, it is essential to minimize the value of the deviation of the roundness of the bearing ring shape not only during grinding but also during turning.

To determine the amount of deformation of the part during machining, it was decided to investigate the accuracy of the shape of the ring of the roller bearing on the outer diameter - the cut that occurs after turning. The bearing ring, the machining of which was studied, is a ring of single-row roller tapered roller bearing 32017X, manufactured by PJSC “SKF Ukraine”. The bearing consists of two clips (outer and inner) and bodies of rotation (conical rollers) connected by a separator (Figure 1a).



a b

Figure 1 – The design scheme: a – bearing32017X;
b – layout of the ring

The outer diameter of the bearing $D = 130$ mm, the inner diameter $d = 85$ mm, the total height $B = 29$ mm, and the height of the holder $C = 22$ mm.

Bearing 32017X is used in the automotive industry of trucks, e.g., models of Mercedes-Benz (Atego, Atego 2), Fiat, MAN, Renault, Volvo, and Isuzu. The billet ring is made by forging (Figure 1b) from steel grade SHKH15SG DSTU 4738:007.

Parts with the set roundness on external diameter were used for tests: 0.27 mm – 5 pieces. Each workpiece in the dividing head was divided into 12 numbered parts. A thin-walled workpiece with a diameter of $130^{+0.5}$ mm (Figure 1b) was installed in the expanded cartridge and clamped by axial forces $P_0 = 25$ kN to check the accuracy of the centering of the workpiece when an axial force pressed it. From the rear headstock side of the lathe, through the dynamometer DS-10, the workpiece was loaded with this effort, which simulated the axial component of the cutting forces, respectively 50, 100, 200, 300, and 400 N.

The experiment used a turning three-jaw chuck with pneumatic cylinder pistons Ø150 mm and Ø95 mm and a floating six-jaw chuck with a pneumatic cylinder piston Ø95 mm (Figure 2a-b) mounted on a machine 1B265NP-6K (Figure 2c), characterized by high requirements serial production. As a result of research, it was necessary to establish the best variant of a cam cartridge that would provide the minimum deformation of preparation.

To determine the amount of deformation of the part during machining, it was decided to investigate the accuracy of the shape of the bearing ring in terms of outer diameter. The test parameter of the shape deviation is not roundness but rather its special case of faceting, which occurs after turning the ring when it is clamped in a turning chuck. The parts for the study were selected directly in the production unit - the turning department of PJSC “SCF Ukraine” in the order of processing without interference with the process. All parts were processed under the same machining conditions, without cooling and with the same clamping force in the chuck [16, 17].

For the study, samples of rings were taken:

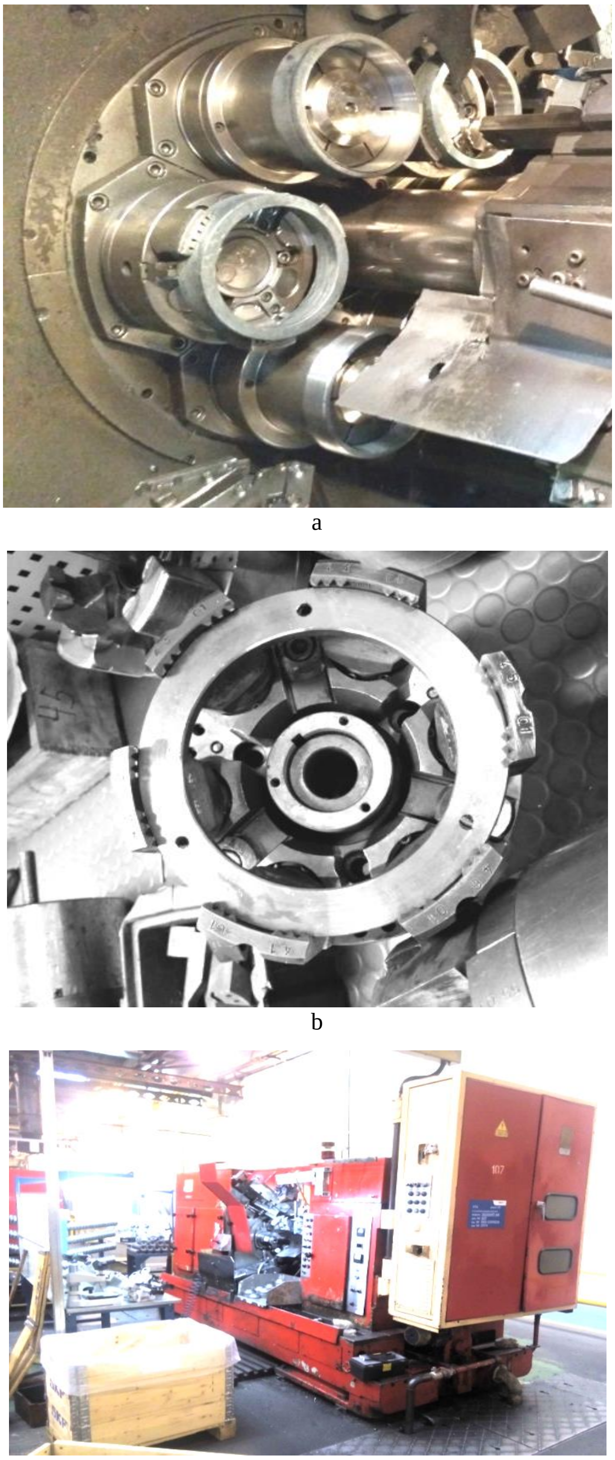
- sequentially, at regular intervals;
- with the same number of parts in the group;
- with covering as many specific causes of variability as possible.

Groups of parts with the same number of 130 pieces each were studied. The parts were selected after turning with clamping in a 3-jaw chuck with a pneumatic cylinder with piston diameters of Ø150 mm and Ø95 mm and a floating 6-jaw chuck with a pneumatic cylinder with a piston diameter of Ø95 mm. The measuring system described above was used for the measurements.

Measurements of the characteristics of the groups of parts were carried out in the sequence of their selection. All parts under study were stored until the statistical evaluation was completed.

For further data analysis, we additionally recorded:

- the start and end time of data collection;
- each intervention in the process of processing parts;
- all stops in the operation of the equipment;
- shift(s)/operator(s);
- unexpected interruptions in the machining process;
- change of workpiece batch.



a

b

c

Figure 2 – Clamping of a ring preparation: a – 3 cam cartridges; b – 6-cam lathe chuck; c – general view of the machine 1B265NP-6K

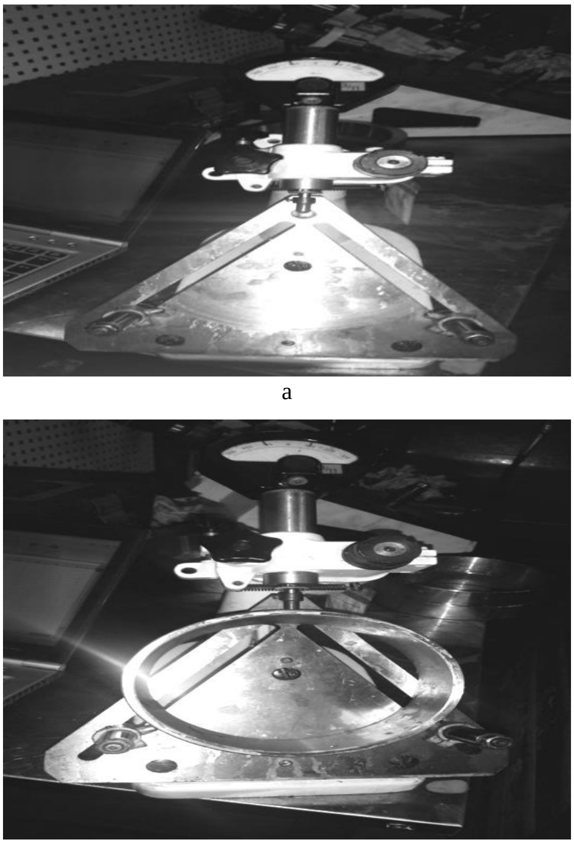
4 Results

Fixing of the workpiece in the cartridges was performed 10 times because the cut has a practical effect on the diameter measurement and may give an erroneous result during the measurement, affecting the actual size of the part during its manufacture. Therefore, it is necessary to rotate the workpiece to measure the correctness of the shape. When measuring the size of the ring, there is a difference between the measured and the actual size for any odd number of faces, so the deviation of the shape of the part can significantly affect its size, measured by the usual method. Determining the correctness of the shape requires measuring the instability – the cut, which is expressed by regularly recurring inequalities. This is especially important to ensure the required accuracy because the cut is essential to any machine tooling [14].

After each clamp, the workpiece was drilled on a machine 1B265NP-6K with a cutting depth $t = 0.5$ mm, speed $n = 378$ rpm, and feed $S = 0.3$ mm/rev. In the process of machining parts, ensuring compliance with the form is almost impossible, so during the control of the outer diameter of the ring was used the method of control using microcator IGPV and installation of the ring in the device PP-1M, which guarantees measurement accuracy (Figure 3).

The IHPV microcator is inserted into the spring measuring head. This gives advantages during the measurement (absence of “dead running” and low friction in the links of the mechanism). Thus, the measuring system used for the measurements was acceptable.

The cut of the workpiece was measured at 12 points on the outer diameter (Figure 4). The roundness of the treated surface was up to 0.15 mm [15]. The obtained values of deviations are within the tolerance and, in some cases, significantly smaller than those provided on the control chart (Table 1).

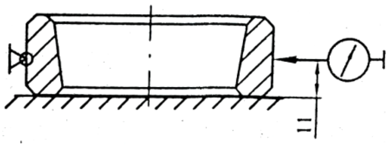


a

b

Figure 3 – General view: a – device PP-1M; b – measuring the bearing ring cut

Table 1 – Accuracy control chart for turning the outer ring of the bearing

Measuring scheme	Measuring mean	Parameters		
		Name	Abbreviation	Tolerance, mm
	PP-1 10IHPV	T-shape deviation-cut	V3D	0.27

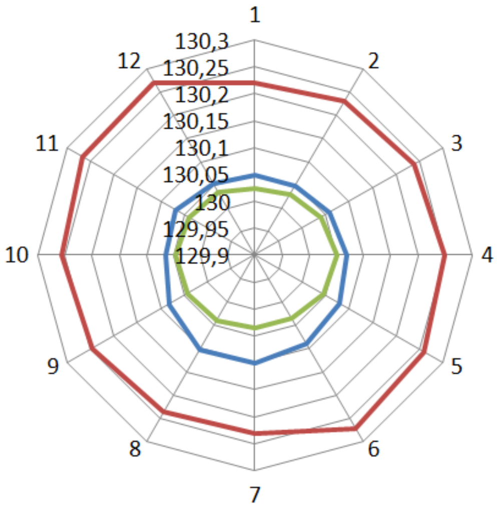


Figure. 4 – Cut the ring at 12 points

Ø95 mm 3-jaw chuck;

Ø150 mm 3-jaw chuck;

Ø95 mm 6-jaw chuck

At the production site, 3 batches of workpieces were sampled with a sample of 130 pieces each, machined on a lathe with clamping in cam chucks of different types. The sample size for the batch of ring blanks is shown in Table 2.

Table 2 – the batch of ring blanks

Lathe chuck	Minimum cut value, μm	Maximum cut value, μm	Span of the sample, μm
3-jaw chuck with 95 mm piston	40	110	60
3-jaw chuck with 150 mm piston	210	290	80
6-jaw chuck with 95 mm piston with replaceable floating cams	20	80	60

After the measurements were taken, the calculations were carried out using the Minitab computer program. Based on the research data, graphs were drawn, one showing the difference between the values of the previous and next samples (a batch of 5 consecutive measured parts), and the absolute value is taken (Figure 5a).

In another graph (Figure 5b), the total number of measurements is also divided into samples of 5 parts, but the difference between the maximum and minimum measurement values is taken from each sample (for example, the processed data for 3-jaw cartridges with piston diameters of 95 mm and 150 mm are shown).

The statistical analysis of the data shows that, according to the criteria of statistical uncontrollability, the production of the ring machining accuracy in the turning operation is maximized when it is clamped in a 6-jaw chuck with a 95 mm piston with replaceable floating cams (Table 3).

Table 3 – Criteria for statistical unmanageability

Criteria for statistical unmanageability	Lathe chuck		
	3-jaw chuck with 95 mm piston	3-jaw chuck with 150 mm piston	6-jaw chuck with 95 mm piston*
Point beyond / on the border of the control boundary	2	1	–
Consecutive dots above or below the midline	5	4	2
The upward or downward trend of consecutive dots	6	4	3
Consecutive dots are close to the midline	6	7	11

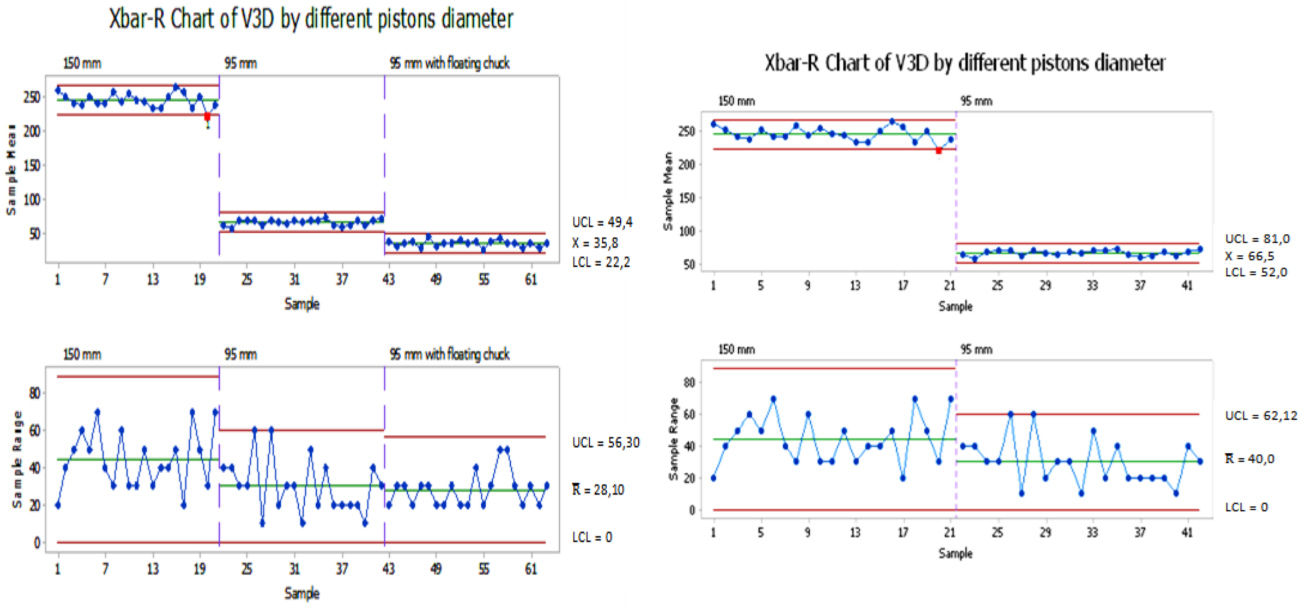
* with replaceable floating cams.

For work using the Minitab program, we filled in:

– for the map of medians X-maps of ranges R (Figure 6a);

– the map of individual values of X-maps of displaced ranges mR (Figure 6b).

The actual deviations of the controlled parameter are as close as possible to the middle of the tolerance field. However, there are cases when unusual curve behavior is detected (both on the R-value/shifted mR map and on the X-value/individual X-value map), characterized by one or more criteria of statistical uncontrollability of the process. For example, in Figure 5, there are cases (marked in red) when the measured value exceeds the values provided by the scale, particularly for workpieces fixed in a 3-jaw chuck with a piston diameter of 150 mm. This indicates the need for immediate intervention in the technological process [18].



a b

Figure 5 – Probability plots for the study of faceting considering the absolute value (a) and the total number of measurements (b)

In order to prevent such phenomena, shortcomings have been identified, and many recommendation measures have been developed to improve the accuracy of turning.

Potential cause of mechanical failure:

1) clamping force is significantly higher than required;

2) incorrectly adjusted pressure in the hydraulic system;

3) imperfect design of the chuck for clamping non-rigid rings.

Recommendations for elimination cause of mechanical failure:

1) use lathe chuck for new designs;

2) replace pistons with a diameter of 150 mm with 95 mm;

3) use a chuck design with a uniform clamping force (floating cams).

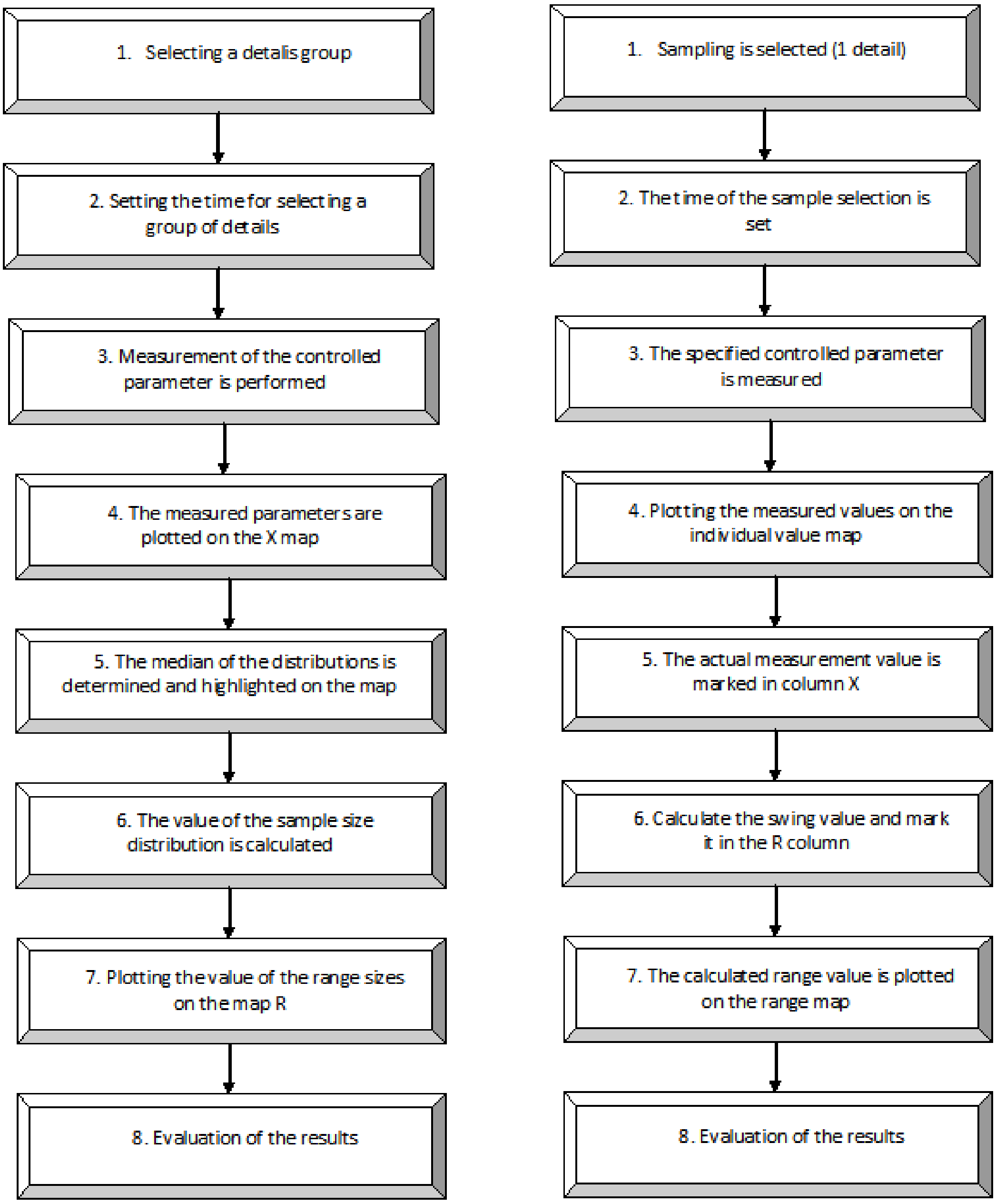
5 Discussion

After analyzing the obtained experimental data, it can be argued that the workpiece in the three-cam cartridge takes a triangular shape, and during the clamp in the 6-cam - hexagonal. Thus, the part obtained after turning will acquire some technological inheritance due to the deformation forces arising during the clamping of the workpiece in the device, which will inevitably affect both the accuracy of finishing and the accuracy and quality of the finished product.

Up to 30 % of the non-roundness of the turning surface treated by turning can be transferred to the finished surface by grinding for the wall thickness of the workpiece within 9 mm. Tests in machining with high cutting forces were performed on manufactured in the amount of 3 parts with increased allowance (cutting depth – 2.5 mm, feed – 0.3 mm/rpm, spindle speed of the machine − 376 rpm, and pressure in the hydraulic system – 10–15 kg/cm²), cutting workpieces before turning is 0.5 mm.

Various designs of clamping cartridges are used for processing parts [1, 4]. In the conditions of automated production of turning chucks, it is necessary to ensure high accuracy and productivity of turning processing [21-24]. In some literature and patent sources, there is insufficient data on the influence of cartridge parameters on the processing error. Using chucks with floating jaws for clamping the workpiece, which also uses a Ø95 mm piston, is advisable. This allows reducing the number of passes, thereby reducing the processing time.

The obtained deviation values are within the tolerance range, and in some cases, the values are significantly lower than those provided by the scale of the sample range. As a result, losses due to defects are reduced by 0.2 % due to increased stability and reliability of fixing parts, and increased processing accuracy.



a b

Figure 6 – Sequence of filling: a – map of medians for $\tilde{X}$-map of ranges R; map of individual values for X-map of shifted ranges mR

6 Conclusions

To increase the accuracy of machining the outer ring of single-row roller tapered roller bearing 32017X on automated lathes for the conditions of PJSC "SKF Ukraine" it is proposed to use replaceable floating cams in the chuck design.

Based on the analysis of experimental and production tests, it was found that the ovality of the treated surface depends on the clamping force on the cams of the chuck. This is determined by the fact that lower clamping forces reduce the friction forces through which the cams move differently, and there is a deformation of the part's surface. In this regard, it is recommended to carry out machining with the minimum clamping forces of the workpiece (25 kN), which are allowed by the cutting force. The stability of centering the workpiece is 0.04–0.05 mm. The best cut size and roundness results are obtained when clamping the workpiece in the piston chuck of a pneumatic cylinder with Ø95 mm.

For chucks with 6 floating cams for clamping the workpiece, which uses a Ø95 mm piston, the obtained values of the deviations of the cut are within tolerance (0.27 mm), and in some places, the values are significantly smaller (up to 0.15 mm) than those provided by the scale sample size. The shape accuracy achieved during the installment is higher in a 6-cam chuck with replaceable floating cams than in a three-cam chuck under the same machining conditions. It was established that up to 30 % of the out-of-roundness of the turned surface could be transferred by grinding the finished surface with a workpiece wall thickness of 9 mm.

The studied quality of bearing ring machining was formed by modern computer technologies, which is especially important for flexible automated engineering production. The accuracy parameters of successively processed parts were checked to confirm the correctness of the machine setup and to establish optimal machining modes (cutting depth – 2.5 mm, feed – 0.3 mm/rpm, spindle speed of the machine – 376 rpm). The actual deviations of the monitored parameters obtained are as close as possible to the middle of the dimensional tolerance field.

Experimental studies can be used to ensure and stabilize the accuracy of the shape of roller bearing rings in turning operations for the conditions of the enterprise PJSC “SCF Ukraine”.

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