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## MONITORING OF THE GRINDING SYSTEM OF FORGED CRANKSHAFTS FOR MARINE ENGINES

## МОНІТОРИНГ СИСТЕМИ ШЛІФУВАННЯ КОВАНИХ КОЛІНЧАСТИХ ВАЛІВ ДЛЯ СУДНОВИХ ДВИГУНІВ

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**Abstract.** The article discusses the problems of controlling the grinding process that arise in the production of forged crankshaft of marine diesel. A set of monitoring measures is presented to assess the possibility of continuing the effective operation of the machine in a grinding system of the product of complex shape and accuracy, unique in terms of material consumption and labor intensity. In the paper, grinding process control problems that occur during the marine diesel engine crankshaft production are addressed. The large size crankshafts have a length of up to 12 m and weigh up to 25 tons, but the final grinding allowance for the diameter is ca. 0.3 – 0.4 mm. To achieve this, very high accuracy of the mechanical parts of the grinding machine is necessary. The study focused on the measurement of parameters such as level, linearity, parallelism, runout and coaxiality of the respective mechanical parts of the grinding machine. The work was performed with grinding machine type DB12500, equipped with Sinumerik 840D control system, as well as measuring and eccentric processing systems. Based on the results, some recommendations were made on the inspection procedure in order to ensure a consisted quality of the produced crankshafts. The grinding tool was a Molemab B126-100639 S.630090 disc type grinding wheel. The choice of chemically inert to the carbon-containing material to be processed and especially hard abrasive tool material (c-BN), as well as a considerable length of the working part of the grinding wheel around the periphery (over 6 m), are an important prerequisite for ensuring tool durability in the cycle of productive and high-quality external processing of specified functional surfaces of considered large crankshafts. Processing allowances were distributed between the preliminary and final grinding transitions with a slight increase (redundancy to ensure accuracy) for crank-pins, which were processed by the second plan. The microgeometric surface quality was controlled using a SurfTest SJ-201P portable surface roughness meter, which avoided the obvious problems of stationary profilometry in the control of large-sized multiple-profile parts, such as shipboard crankshafts.

The obtained roughness parameters after grinding ( $Ra \leq 0.4 \mu\text{m}$ ) were found highly satisfactory, allowing effective polishing afterwards up to the level of  $Ra 0.3 \mu\text{m}$  necessary for the main functional surfaces. The work performed can be considered as a methodological prototype of monitoring in roadmaps for examining the state of the accuracy parameters of grinding machines and the level of microgeometric quality of processing crankshafts.

**Key words:** crankshaft; grinding; roughness; machine tool; runout; linearity; parallelism; monitoring.

**Анотація.** У статті розглядаються проблеми управління процесом шліфування, що виникають під час виробництва кованого колінчастого вала суднового дизеля. Представлений комплекс моніторингових заходів для оцінки можливості продовження ефективної експлуатації верстата в системі шліфування складного за формою і точністю, унікального за матеріаломісткістю і трудомісткістю виробу. Колінчасті вали великого розміру мають довжину до 12 м і важать до 25 тонн, але допуск на остаточне шліфування для діаметра становить 0,3–0,4 мм. Для цього необхідна дуже висока точність механічних деталей шліфувального верстата. Дослідження було зосереджено на вимірі таких параметрів, як площинність, лінійність, паралельність, биття і співвідношення відповідальних за вихідну точність механічних частин шліфувального верстата. Робота виконана зі шліфувальним верстатом типу DB12500, оснащеним системою управління Sinumerik 840D, а також системами вимірювання та ексцентричної обробки. На підставі отриманих результатів були зроблені деякі рекомендації з процедури перевірки з метою забезпечення стабільної якості випуску колінчастих валів. Шліфувальним інструментом був шліфувальний круг дискового типу Molemab B126-100639 S.630090. Вибір хімічно інертного до оброблюваного матеріалу з вмістом вуглецю і водночас особливо твердого абразивного інструментального матеріалу (с-BN), а також значна протяжність робочої частини шліфувального круга по периферії (понад 6 м), є важливою передумовою забезпечення стійкості інструменту в циклі продуктивної і якісної зовнішньої обробки заданих функціональних поверхонь розглянутих великогабаритних колінчастих валів. Припуски на обробку розподілялися між попереднім і чистовим переходами шліфування з деяким збільшенням (резервуванням забезпечення точності) для шатунних шийок, обробка яких велася другим планом. Мікрогеометричну якість поверхні контролювали за допомогою портативного вимірювача шорсткості поверхні SurfTest SJ-201P, що дозволило уникнути очевидних проблем вимірювання профілю в задачах контролю великогабаритних деталей складної ступінчастої форми, якими є суднові колінчасті вали. Отримані параметри шорсткості після шліфування ( $Ra \leq 0,4 \mu\text{m}$ ) були визнані вагомою мірою задовільними, що дозволило після цього ефективно полірувати до необхідного за основними функціональними поверхнями рівня  $Ra 0,3 \mu\text{m}$ . Виконана робота може розглядатися як методичний прообраз моніторингу в дорожніх картах експертизи стану параметрів точності шліфувальних верстатів і рівня мікрогеометричної якості обробки колінчастих валів.

**Ключові слова:** колінчастий вал; шліфування; шорсткість; верстат; биття; лінійність; паралельність; моніторинг.

## PROBLEM STATEMENT

A failure of the marine engine crankshaft may threaten the life of the shipboard personnel and passengers, so there is a need to continually improve the technology, quality control, and the inspection of the machine tools' performance in its production. The crankshaft is a crucial element of the marine engine, and special standards prescribe how they must be projected, e.g. the one issued by PRS Executive Board [1]. Nowadays, there are three main technologies for large marine diesel engine crankshaft fabrication, which produce assembled crankshafts, semi-built crankshafts and fully forged ones [2]. The first two technologies have crankshaft parts that joined together with the shrink-fitting method [3]. A critical step in the manufacture of forged crankshafts is the grinding of its sidewalls [4].

## LATEST RESEARCH AND PUBLICATIONS ANALYSIS

Grinding of sidewalls of forged crankshafts can be implemented by applying several strategies, e.g. axial

plunge grinding, axial face grinding, and multi-step axial face grinding [4]. The rising demands on quality also force the improvement of grinding performance and are driving the development of machines for grinding [5]. Grinding parameters have direct impact on the integrity of machined surfaces and their characteristics, such as residual stresses, surface roughness and dimensional stability [6]. Improper grinding was reported to be a source of misalignments in journals, high stress concentration, and high surface roughness [7]. Shen et al. [8] examined the elastic deformations of the large size crankshafts generated by grinding process, while Torims et al. [9] analyzed the influence of grinding parameters on the surface texture formation in the reparation process of marine diesel engine crankshafts. Hashimoto et al. pointed out that the improvements aimed to achieve fuel efficiency raise additional demands on the superfinishing of the crankshafts [10]. Importance of the cooling conditions was analyzed by Maruda et al. [11]. Tian et al. [12] proposed a portable power monitoring system for grinding process.

## SEPARATION OF PREVIOUSLY UNSOLVED PARTS OF THE GENERAL PROBLEM

The customer sets very high demands on the surface topography with  $Ra < 0.3 \mu\text{m}$ , which is almost impossible to obtain with the grinding technology. Therefore, hand polishing is applied after grinding. Typically achievable  $Ra$  parameters after grinding are between  $0.5$  and  $1.4 \mu\text{m}$ , while after polishing it lays between  $0.1$  and  $0.3 \mu\text{m}$  [13]. However, hand polishing has very limited impact on the surface, so the grinding process has to prepare the surface as efficiently as possible. The study below is dedicated to the grinding process of the crankshaft machining, as well as the inspection procedures aimed to control the performance of the grinding machine.

**The article aim** – is to identify to-do list and test a set of monitoring measures to make a decision to renovation or continued operation of the machine in the grinding system of the forged crankshaft of a marine engine which is a unique product in terms of material consumption and laboriousness.

## METHODS, OBJECT AND SUBJECT OF RESEARCH

Grinding is one of the final machining processes of the crankshaft fabrication. Main journals and cranks obtain the dimensions close to the upper tolerance, so that the surface can be finished by hand (lapping and polishing procedures). The examined grinding process was performed with a grinder DB12500 type (Fig. 1) equipped with the control system Sinumerik 840D, measurement system Marposh and eccentric machining system Pendulum.



Fig. 1. The DB12500 grinding machine

The grinding tool was the disc-type grinding wheel Molemab B126-100639 S.630090 shown in the Fig. 2. Its diameter was  $\varnothing 2000$  mm, and width  $B = 140$  mm, and it was covered with the cubic-form boron nitride (c-BN). The use of large-diameter grinding wheels with abrasives of the highest hardness (diamond, cubic boron nitride) in various tasks of precise shaping makes it possible to carry out preliminary and final grinding of operationally

responsible external surfaces in one processing cycle, due to the increased durability of the tool in the technologically correctly built cycle, for example, when grinding rolls of rolling mills after surfacing with wear-resistant wire material [14]. The maximal cutting velocity and rotational speed were  $V_{\text{max}} = 50$  m/s and  $n_{\text{max}} = 473$  rpm, respectively.



Fig. 2. The Molemab B126-100639 S.630090 grinding wheel during the operation

Like in any machining technology, the final surface quality was dependent on the geometry and performance of the “machine – tool – workpiece” system. For any type of fabricated crankshaft, the grinding operations sequence has been assumed to be the same, namely, the main journals were to be grinded first (main axis of the crankshaft), so the final dimensions were achieved, and then the crank-pins were grinded. In general, the grinding process can be described as follows:

- The grinding allowances of the diameter were ca. 1 mm, maximally up to 1.5 mm. It was more desirable to leave larger allowances on the crank-pins, in order to avoid the increased uncertainty when the angle of the reference crank-pin was measured.
- After initial grinding of all the main journals, the fine grinding was initiated.
- The allowance for the fine grinding was ca. 0.3-0.4 mm on diameter.
- Supporting tailstocks are always put down under the grinded main journal. After grinding, the journal is again supported, and the position of the crankshaft is corrected on the base of flexometer indications.
- High pressure washing of the grinding disc after each operation is performed in order to prolong durability of the tool.

The above procedure is presented schematically in Fig. 3. It is crucial that, after the initial grinding of all the main journals, Marposh device measurements are processed by and form corrections are performed, so that

final grinding commences only after the main axis accuracy is assured.

**The object of the research** is marine engine forged crankshaft grinding system. **The subject of the research** is the machine model DB12500 in the grinding system of the forged crankshaft of a marine engine using the tool model Molemab B126-100639 S.630090 from superhard abrasive based on cubic boron nitride.

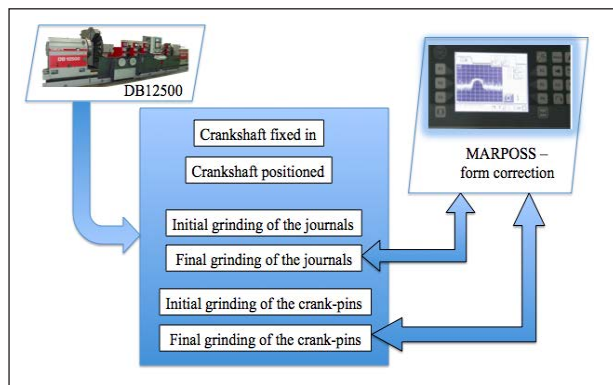


Fig. 3. Crankshaft grinding procedure

The grinding machine DB12500 is equipped with the measurement system Marpos, which consists of three main units:

- Automatic system Marpos Wheel Balancing designed to continually supervise the balance of the grinding disc while it is in motion.

- The main measurement system Marpos Post-process designed to measure form deviations of the main journals and crank-pins. The unit has three supporting points and the specially constructed arm, Fenar-L, which enables the measurement of both main journals and crank-pins. The sensor collects 3600 points per rotation and is synchronized with the control system Sinumerik 840D. The measured values are averaged down to 360 points using one of the delivered algorithms. These points are the basis for the form compensation table correlated with the angle position of the measured pivot. The form correction is performed using the perpendicular support with defined virtual axis. Resolution of the device is 0.001 mm.

- The third unit is a Marpos Monitoring equipped with the ultrasonic microphones. It is designed to monitor the slot between grinding disc and grinded material (the GAP function) in order to control the contact between the tool and the ground material.

In order to maintain the consistent performance of the grinding machine, it was checked regularly with additional devices. In our case, it was an electronic level type LE051 produced by Microplan. It is equipped with a digital/analog display, and its internal mechanism is submerged in an oil-bath box. Achievable sensitivity of the level LE051 is 1  $\mu\text{m}/\text{m}$  or 0.2 second of arc. It has 5 measuring scales

providing resolutions from 250  $\mu\text{m}/\text{m}$  per division down to 1  $\mu\text{m}/\text{m}$  per division. The data can be transferred to a PC through the serial connections RS-232.

Linearity of the bed with the fixed headstocks of the grinding machine was inspected using the collimator device with a string and measuring magnifier.

Moreover, the parallelism of the bed with fixed headstocks and the support was inspected. In the measurement, the electronic dial gauges (produced by Kor dt) were used, with a resolution of 0.001 mm. They were placed on the grinding machine support and bed.

Similar electronic dial gauges were used in the measurement of the grinding disc runout as well as of the fixed headstocks. In the latter case, both radial and axial runout was measured. Additionally, the following parameters were inspected:

- parallelism between the axes of the disc cone during the headstock movement,
- distance between the vertical positions of the disc and headstock axes,
- runout of the disc cone,
- and the coaxiality of the fixed headstocks.

Methodological issues of measurement geometric accuracy parameters – such as level, linearity, parallelism, runout and coaxiality – of the respective mechanical parts of the grinder DB12500 equipped with the control system Sinumerik 840D and measurement system Marpos are discussed and illustrated in more detail in our work [15].

Since the roughness of the crankshaft surface is a very important parameter after grinding, it was also measured. On-machine and in-process surface metrology is important for quality control in manufacturing of precision surfaces [16].

According to the documentation, the main journals must have a very smooth surface with  $Ra < 0.3 \mu\text{m}$ , so the grinding prepares the surface leaving only little deformation that can easily be removed during polishing. After grinding, the  $Ra$  parameter was measured with the portable surface roughness tester Surf test SJ-201P. It was chosen because of the obvious difficulty with applying the stationary profilometer to a huge detail such as the crankshaft 18W46 type. The most important parameters of SJ-201P device are as follows:

- measuring range 350  $\mu\text{m}$  (from -200 to +150  $\mu\text{m}$ ),
- diamond stylus tip of radius 5  $\mu\text{m}$ ,
- sampling length 0.25 mm, 0.8 mm, 2.5 mm,
- displaying range from 0.01  $\mu\text{m}$  to 100  $\mu\text{m}$ ,
- resolution is dependent on the measuring range, with the highest being 0.01  $\mu\text{m}/10 \mu\text{m}$ ,
- data output via RS-232 interface unit.

As such, this device was considered sufficient to inspect the roughness of the crankshaft surface both after grinding and later, after hand polishing.

## BASIC MATERIAL AND DISCUSSION

The results of inspection of the abovementioned parameters – initial (June) and after 5 months of operation

(November) – are presented and discussed in the respective subsections below.

**Level declinations.** Fig. 4a,b presents the results of level measurements obtained at different measuring points along the bed with fixed headstocks, in June and in November. The measurement was performed both in parallel and perpendicular directions.

The general observation is that after 5 months, the level deteriorated, so its regulation was needed to avoid the dimensional errors in the grinding process. Moreover, it is seen that the dispersion of the results is larger in the parallel direction (between 0 and 0.03 mm/m in June and between 0.03 and 0.16 mm/m in November) than in the perpendicular measurement (between -0.005 and 0.005 mm/m in June and between 0.175 and 0.24 mm/m in November). However, the dispersion of the respective results obtained both in the parallel and perpendicular directions was smaller in June than in November. It was concluded that the most instable level was the parallel direction, therefore it was recommended to check it more frequently, with the measurement taken at a minimum 3 points, to check for any trend.

Similarly, the bed level declination was checked along the support axis, both in the parallel and perpendicular directions. Fig. 4c,d shows the positioning of the electronic level and the results of the measurement. Again, the parallel direction displays a larger dispersion, particularly in the June measurements. The November measurement re-

sults are biased towards the negative values and are more dispersed than those of June. Thus, it can be recommended that the support axis level is checked and corrected more often, and the measurement should be performed at all 13 measuring points.

**Linearity and parallelism deviations.** The measurement results for the linearity of the bed with fixed headstocks are presented in Fig. 5a. On the other hand, Fig. 5b presents the results of the parallelism measurement between the bed and the support. The measurements were performed at 11 points distanced ca. 1 m apart, and each point was given a subsequent number.

It should be noted that the linearity measurement in June revealed deviations between -0.01 and 0.01 mm, while in November twice as larger, namely, between -0.02 and 0.02 mm. Nevertheless, the latter is still acceptable, since the permissible non-linearity of the bed with the fixed headstocks is 0.02 mm per 1000 mm, but the obtained results indicated immediate need of correction. It was also observed that the right part of the bed (points from 1 to 5) tended to reveal positive values of non-linearity, while negative values dominate in the left part.

In the case of parallelism deviations, the trend is clear and a correction of the mutual position of the bed and support can easily be made.

**Other measurement results for the grinding machine** are shown in Table 1.

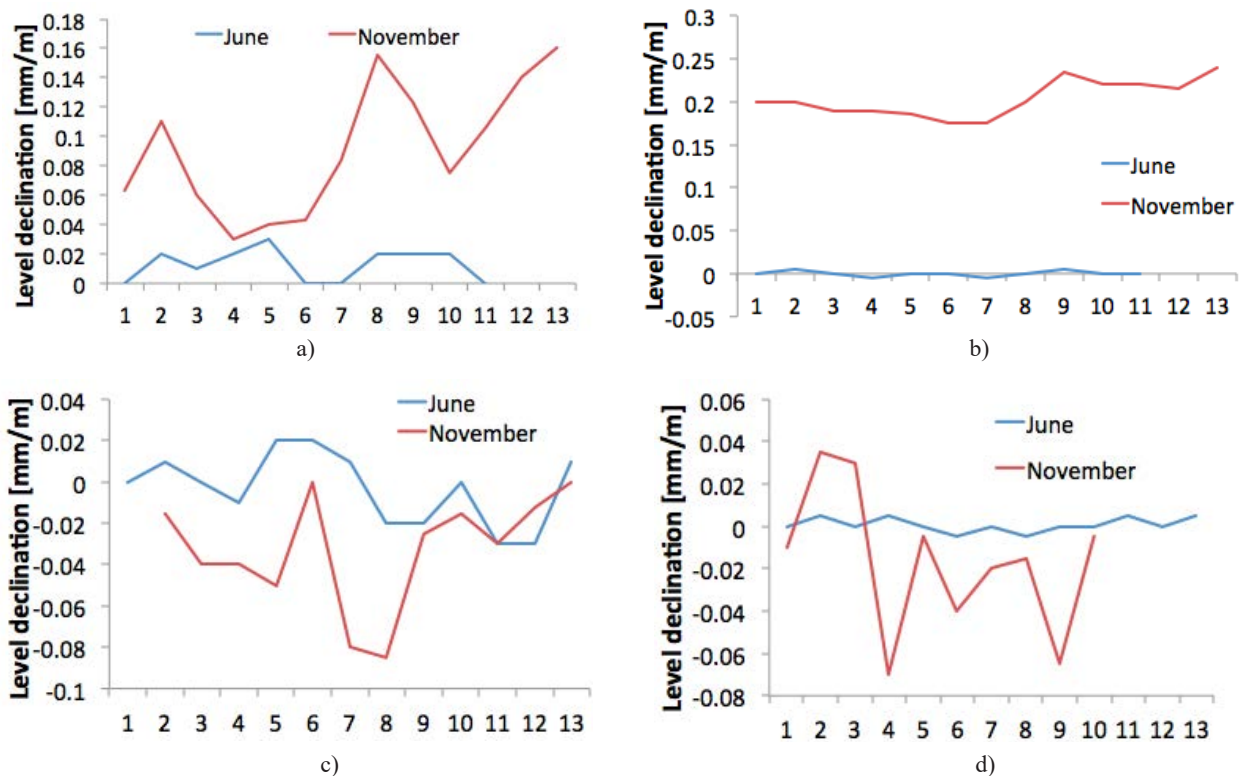


Fig. 4. Parallel (a,c) and perpendicular (b,d) level checks of the bed: with fixed headstocks (a,b) and in the support axis (c,d)

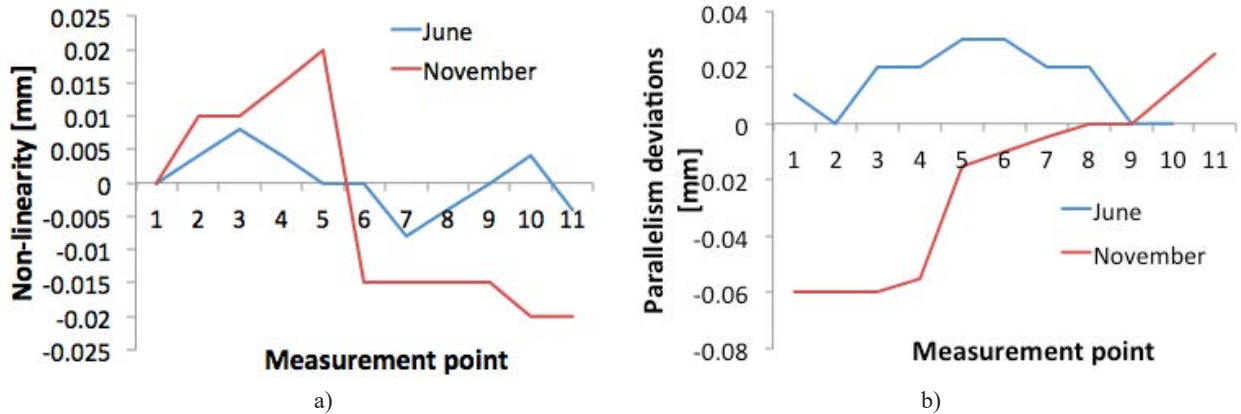


Fig. 5. The measurement results for the bed with the fixed headstocks: (a) linearity and (b) parallelism between the bed and the support

Table 1. Measurement results for various features of the grinding machine

Measured feature	Measurement result	Permissible error
Grinding disc perpendicularity [mm/mm]	0.010–0.015/300	0.02/300
Headstock S1 runout [mm/mm]	0.010–0.025/350	0.025/300
Headstock S2 runout [mm/mm]	0.010–0.025/350	0.025/300
Disc cone coaxiality [mm/mm]	0.007–0.020/300	0.03/300
Vertical position of the disc and headstock axes [mm/mm]	0.25/920	0.40/1000
Disc cone runout [mm]	0.001-0.002	0.005
Headstocks coaxiality [mm]	0.01–0.02	0.02

The presented results proved the proper performance of the grinding machine. In some cases, where the values approached the permissible error, it indicated the need for calibration of the machinery. Since the quality control of the produced crankshafts confirmed the final form and di-

mension tolerances obtained, the inspection procedure of the grinding machine geometry was deemed satisfactory with the addition of the improvement recommendations discussed above.

**Roughness after grinding.** The examples of the distribution of roughness measurement results for the main journals CG (10 journals, measurements at 4 points on each) and the crank pivots CK (9 pivots, measurements at 4 points on each) after grinding are shown in the Fig. 6.

The results are highly satisfactory, so that the final roughness below  $Ra = 0.3 \mu m$  is easily achievable through hand polishing.

**CONCLUSIONS**

The presented study aimed to evaluate the inspection procedure of the grinding machine involved in the marine diesel engine crankshaft production process. It was found that the most unstable parameter was the level of the bed with fixed headstocks in the parallel direction. Based on this finding, it is recommended to monitor the fixed headstocks' bed level in shorter intervals, e.g. every 3 months, not necessarily comprehensively, but with measurements taken at a minimum of 3 points to check the trend. Addi-

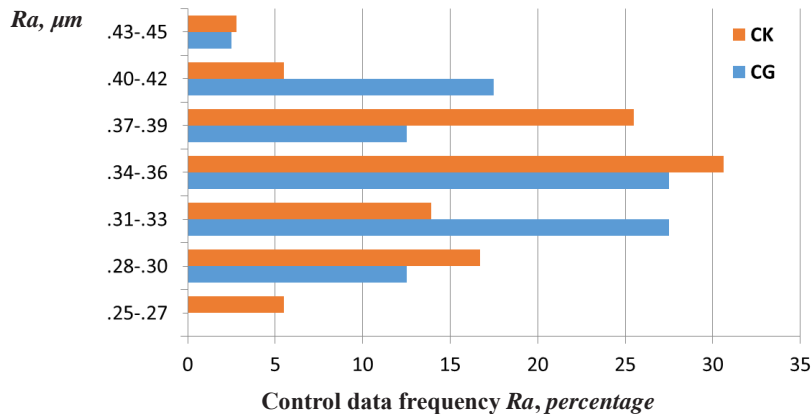


Fig. 6. The distribution of roughness measurement results for the main journals (CG) and the crank pivots (CK)

tionally, it was recommended that the support axis level is checked and corrected at least every 3 months. Measured linearity of the bed with the fixed headstocks revealed an immediate need for correction, no such correction of the inspection procedure was considered necessary. Under the above conditions, the roughness obtained after grinding was found to be highly satisfactory.

The completed work can be considered as a methodical prototype of monitoring in roadmaps for examining

the state of the accuracy parameters of grinding machines and the level of microgeometric quality after processing of crankshafts. The sequence of monitoring activities, their composition and control schemes are specified by further studies in the production conditions. The development of a roadmap for the examination of the state of the machine and the level of microgeometric quality of processing expands the possibilities of flexibility and reliability in organization of production, increasing its stability and efficiency.

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