МЕХАНІЗАЦІЯ, АВТОМАТИЗАЦІЯ ТА РОБОТИЗАЦІЯ

MECHANIZATION, AUTOMATION AND ROBOTICS

UDC 621.9.06-529.004:658.562

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USE OF SHEWHART CONTROL CHARTS TO ENSURE PRODUCT QUALITY AND OPTIMIZE THE MAINTENANCE SCHEDULE FOR CNC METAL-CUTTING MACHINES. CASE STUDIES

Purpose. *On the example of a CNC machine DAEWOO PUMA 600M, using statistical methods of quality management, in particular, Shewhart charts, a scheme for maintenance and repair of machine tools in order to reduce operating costs was work out.*

Research methods. *For the case under study, from each batch of 30 Wheel units, the quality control department monitored the deviation from the nominal value of the most critical accuracy parameter, the mounting diameter for the rolling bearing outer ring, for five random products. A total of 60 such samples were taken. The mounting surface diameter was monitored using three-point precision intalometer. Thus, for a total sample of 300 units, Shewhart control charts for the center and range positions were built and statistical analysis was performed the purpose of which is to identify special trends. In addition, the errors correction log entries were analysed in a similar way to determine whether a positioning error was present.*

Results. *It has been shown that the use of Shewhart's control charts allows assessing the actual state of the machine tool equipment. Based on this fact, a model of maintenance and repair of CNC machines using statistical data analysis is proposed. The application of the proposed model to the entire maintenance and repair cycle can significantly extend the inter-repair period for CNC machines. The number of repair activities was reduced by 35–50 %. At the same time, the cyclicity of operations provided by the manufacturer's technological routine for this type of machine tool remains unchanged, the equipment utilisation rate increases, and it is possible to reduce the required number of repair service personnel.*

Scientific novelty. *The relationship between the results of the cutting process, which are determined by Shewhart's control chart, and the state of equipment is established to formulate maintenance and repair measures.*

Practical value. *The proposed scheme for organizing the maintenance and repair of CNC machines based on statistical analysis using Shewhart charts provides a significant reduction in the cost for their operation.*

Key words*: range, control limits, special trend, variation, distribution, process capability index, actual state of equipment, inter-maintenance period.*

Introduction

The condition of metal-cutting equipment, as shown in the works of Kusyi et al. [1] and Usubamatov et al. [2], has the greatest impact on the quality of the products machined on it. Based on this, the maintenance and forecasting of the serviceable condition of equipment and other elements of the production system, according to Lee et al. [3]

DOI 10.15588/1607-6885-2025-2-10

has a direct impact on its productivity and other economic aspects. In today's economy, due to the development of Industry 4.0 technologies, industrial companies need approaches that will be able to predict the behavior of equipment and prevent the occurrence of emergencies through its maintenance.

Carrying out a set of works on maintenance and repair of machines (MR) is always associated with the need to stop the equipment, i.e., its exclusion from the production cycle. There are three main strategies for managing maintenance and repair [4]:

- Scheduled preventive maintenance (SPM);
- maintenance according to actual condition (MAC);
- event-driven repair/maintenance (EDRM).

The consequences of choosing one or the other approach, associated with an increase in the inter-maintenance period, will range from cost overruns for MR to sudden failures of critical elements of metal cutting equipment with damage to the workpiece at that moment. Both extreme approaches are costly for the budget and the company's image. Therefore, according to Guler et al. [5], there is a desire for companies to combine the benefits of all major MR strategies by using combined maintenance (CM), aimed at both reducing the overall amount of maintenance and maximizing equipment life and reducing the costs associated with increased inter-repair periods and reduced frequency of event-based repair/maintenance.

Analysis of research and publications

Modern systems of maintenance and repair of industrial equipment have been developing for a long time and have gone through a number of evolutionary stages [6]. At the beginning of the industrial era, equipment maintenance and repair were mainly performed by production managers or experienced workers without formalized systems. The lack of standardization and organization led to irregular maintenance and long downtimes.

In the 1950s and 1960s, with the development of technology and automation, the concept of predictive maintenance emerged. It involved regular preventive maintenance and inspections of equipment to prevent breakdowns and reduce the likelihood of failures.

In the 1970s and 1980s, computer systems for maintenance planning and control began to be actively used, which marked the beginning of programmatic maintenance and diagnostics. Programs allowed creating work schedules, monitoring equipment status, and providing data for diagnosing breakdowns. The introduction of electronics and sensors allowed for automatic monitoring of maintenance [7].

The concept of Total Productive Maintenance (TPM) originated in Japan in the late 1980s [8]. It involves the broad involvement of personnel at all levels in the maintenance and support of equipment, and emphasizes proactive maintenance and breakdown prevention.

With the development of technology in the context of Industry 4.0, industrial equipment maintenance and repair systems are becoming increasingly automated [7]. Sensors and transducers monitor the condition of equipment in real time, and the data is transferred to cloud systems for analysis and decision-making. This makes it possible to predict breakdowns, plan maintenance and repairs based on actual data, which is one of the principles of ISO 9000 [9] quality management. Adherence to these principles can significantly increase the efficiency of industrial equipment operation.

Modern industrial maintenance and repair systems continue to evolve and integrate new technologies such as artificial intelligence, data analytics, and autonomous systems [7, 8, 10, 11]. The entire range of equipment maintenance and repair operations can be divided into two groups:

1. SPM, mainly related to the prevention of failures and damage;
2. work to identify and eliminate defects that caused failures and damage.

In practice, there may be different ratios between these groups of works, depending on the adopted optimization criterion and the chosen strategy of maintenance and repair. The cost of maintaining equipment in working condition in the cost of production reaches 6–20 %, so the main requirement for the operation process is to ensure the highest probability of maintaining the performance of the functional system (equipment, unit, assembly unit) within a certain period of time at limited costs [12, 13]. This approach is realized through the use of combined maintenance (CM).

The concept of such maintenance is that different technologies are used at each time horizon of MR planning: SPM or MAC. For example, on the long-term planning horizon, the indicators of the SPM are taken as a basis. On the operational planning horizons, the MAC is used, while the MR indicators are determined based on the statistical analysis of equipment condition measurement data, on the basis of which a financial reserve is formed [14]. In accordance with the CM, as the planning horizon is shortened, the planned MR indicators are consistently refined. The basis for such refinement is data on the actual condition of the equipment, its technological conditions, as well as the implementation of MR plans in previous periods.

The use of the CM allows to increase the equipment utilization rate without a significant increase in costs, helps to plan the corporate budget more correctly and should be based on the use of actual data in accordance with the principles of quality management set forth in ISO 9000 [9]. One of such means of collecting and analysing information is Shewhart control charts (SCC). As demonstrated by Malindzakova et al. [15], under conditions of stable and repeatable production, the above are an effective means of providing information on the variability and reliability of the production process that is the object of monitoring. They identify random variations and violations of control limits of quality indicators.

The data for analysing the system functioning can be both sensor data that are part of the equipment and data obtained during measurements of the equipment technological state or measurements of product parameters [16, 17].

DOI 10.15588/1607-6885-2025-2-10

The use of systems for data, obtained from various sources, analysis and the application of statistical methods for processing these data allow creating a subsystem with which to obtain control markers of mechanism state. The basis of such a subsystem, can be the above-mentioned SCC or process behaviour charts. A control chart is a special type of time diagram that enables to identify the points of the process that leave the steady state due to natural variability, for further determination of the causes of deviation and its elimination, determination of the process capabilities (controllability), identification of fluctuation points and process quality forecasting [18]. The use of charts assumes that the controlled characteristic obeys the normal Gaussian distribution. Deviations from the normal distribution indicate the presence of a powerful factor that determines the actual shape of the distribution, which is a separate subject of analysis [19, 20, 21]. A detailed technology of analysis using the SCC is contained in ISO 7870-2:2023 [22].

Objective of the study

On the example of a CNC machine DAEWOO PUMA 600M, using statistical methods of quality management, in particular, Shewhart control charts: identify the sources and methods of data collection; determine the existence of a correlation between deviations from the nominal of the machined part critical dimension, the positioning error of the machine tool and its physical condition for the integration of combined maintenance technology; to work out a rational scheme for machine tool maintenance and repair, based on its actual state, in order to reduce operating costs.

Research material and methods

The PUMA 600M model CNC machine, defined as the object of study, produced the identical product – the "Wheel" item throughout the entire research cycle (see Fig. 1).

Figure 1. Object of the study – Daewoo PUMA 600M CNC machine

During the study, using three-point precision intalometer with the dimensional resolution of 0.001 mm., the deviation from the nominal value of the most critical accuracy parameter of the "Wheel" item - the mounting diameter of the outer ring of the rolling bearing ø230M7$_{(-0.045)}$ - was monitored (see Fig. 2). The material to be machined is 42CrMo4 steel of hardness HRC 45-55.

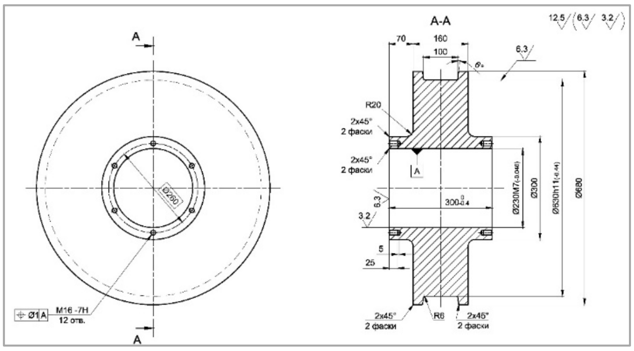


Figure 2. The "Wheel" item drawing

The following methods can be used to obtain accuracy data for the PUMA 600M metal cutting machine:

1. Geometric analysis.
2. Measurement of positioning error.
3. Monitoring of dynamic characteristics.
4. Statistical analysis.

For the selected type of equipment, a combination of methods 1, 2 and 4 is most suitable, which best meets the production requirements and goals of assessing the accuracy of the machine, taking into account the available resources, the type of measurements and their accuracy that must be achieved to complete the task. The data for analysis includes the results of the controlled dimension measurements from samples that are randomly taken by the quality control department on a daily basis (geometric analysis), as well as errors correction log entries, which indirectly indicate the physical condition of the machine in the context of positioning error.

For the case under study, the quality control department monitored the parameters of n = 5 random products from each 30-unit batch, and m = 60 such subgroups were taken. Thus, the total sample size is N = 300 products.

The dynamics of machine condition monitoring is set by the required data collection period, which is determined based on the technical characteristics of the machine and its operating mode. Based on the requirements of the operational documentation, for the purpose of this study, data were collected during 1120 hours of machine operation. Thus, the time for processing one group is about 18.65 hours. At the same period a total of 20 correction activities were made based on the machining of test parts from the results of three measurements.

According to the recommendations of ISO 7870-2:2023 [22], SCC for the centre position and for the range were selected. The lower (LCL) and upper (UCL) limits of the centre position are determined from equations (1) and (2) respectively:

$$\boldsymbol{LCL = \bar{\bar{X}} - A_2 R}, \quad (1)$$

$$\boldsymbol{UCL = \bar{\bar{X}} + A_2 R}. \quad (2)$$

DOI 10.15588/1607-6885-2025-2-10

Here, $\bar{\bar{X}}$ is the average value determined from *m* subgroups of *n* elements each according to Equation (3); *R* is the average range of groups determined by Equation (4).

$$\bar{\bar{X}} = \frac{1}{m \cdot n} \sum_{i=1}^{m} \sum_{j=1}^{n} X_{ij}. \qquad (3)$$

Where X_{ij} – measurement results; *i* - subgroup number; *j* - product (measurement) number in the subgroup.

$$R = \frac{1}{m} \sum_{k=1}^{m} \left(X_k^{max} - X_k^{min} \right). \qquad (4)$$

Here, X_k^{max} and X_k^{min} are the maximum and minimum measurement results in subgroup *k*, respectively.

The lower and upper limits of the range are determined by equations (5) and (6), respectively:

$$R_{LCL} = D_3 R, \qquad (5)$$

$$R_{UCL} = D_4 R. \qquad (6)$$

The coefficients in equations (1), (2) and (5), (6) for the subgroup of volume *n* = 5 according to [22] are equal to $A_2 = 0.577, D_3 = 0, D_4 = 2.114$ and for the subgroup of volume *n* = 3 (error correction) - A_2 = 1.023, D_3 = 0, D_4 = 2.574.

It should be noted that the magnitude of *R* reveals an undesirable variation within the group, and the mean $\bar{\bar{X}}$ reflects the stability of the process as a whole, including variations between groups.

For the purposes of this study, the conformity of the obtained samples' distribution to the normal distribution law was checked using the Kolmogorov-Smirnov type criterion, taking into account the sample estimation of the theoretical distribution parameters [23]. This criterion is stronger than the traditional one. The verification is carried out on the basis of the inequality (7):

$$\sqrt{N} \cdot \sup\left(\left| F(t_i) - \hat{F}(t_i) \right| \right) \leq C(q). \qquad (7)$$

Where $F(t_i)$ *and* $\hat{F}(t_i)$ - accordingly, the values of the theoretical and empirical integral distribution function; $C(q)$ - critical value of the criterion for confidence probability *q*.

For *q* = 0.95 - $C(q) = 0.895$

Research results

According to the existing regulations at the enterprise, every 350 hours of machine operating time, technical inspection (TI) is carried out to control the main parameters of the machine's units: vibration control, geometric parameters control, technological accuracy control, thermal imaging control, and output quality control. The complex of maintenance activities takes 1 shift and costs 12 man-hours. No adjustment or repair operations are performed during the maintenance.

Once every 3 years, based on the results of the TI, medium repairs are carried out with the replacement of parts with an expired service life. The machine is overhauled once every 10 years. The full repair cycle takes 10,000 hours.

To develop an optimal MR strategy, along with the performance of work according to the schedule, deviations of critical dimension were monitored and the data obtained were used to build control charts of mean absolute deviations (X-chart) as well as that of a range (R-chart), shown in Fig. 3. Control charts demonstrate whether the production process is stable. To control the variability of the machine state by the key parameters according to ISO 7870-2:2023 [22], it is proposed to use the criteria for identifying special trends of parameters.

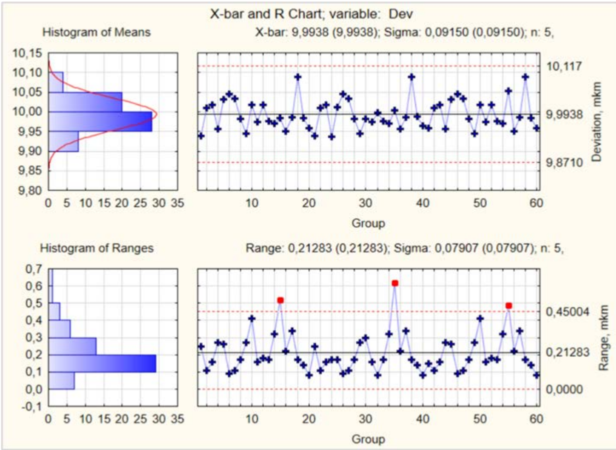


Figure 3. Shewhart control charts of Means and Ranges for "Wheel" item mounting diameter measurements

The SCC of the correction Means and Ranges, based on the error correction log entries, are shown in Fig. 4. The distribution of mean error corrections conforms to the normal distribution law.

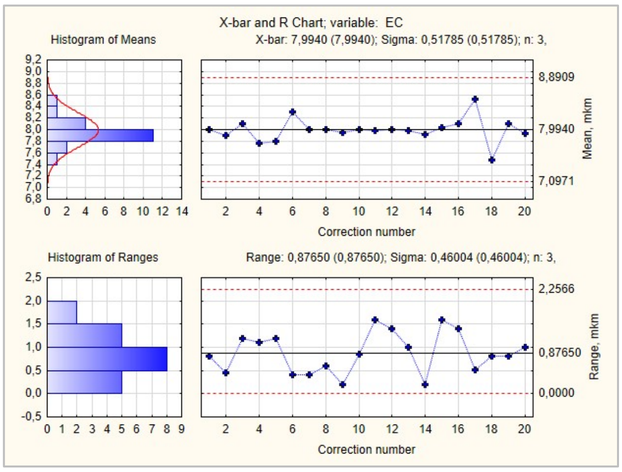


Figure 4. Shewhart control charts of Means and Ranges for error corrections

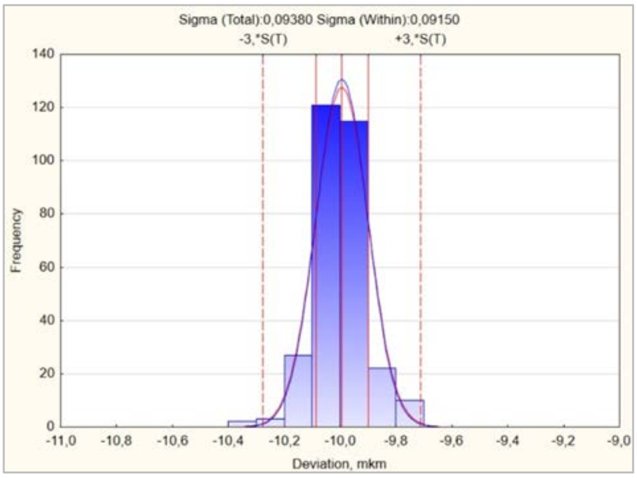
Additional geometric analysis tools that can also be performed as data is accumulated are the analysis of the controlled dimension deviation distribution and the analysis by the process capability index (PCI) - C_p calculated by the Eq. (8)

$$C_p = \frac{UAL - LAL}{6S}. \qquad (8)$$

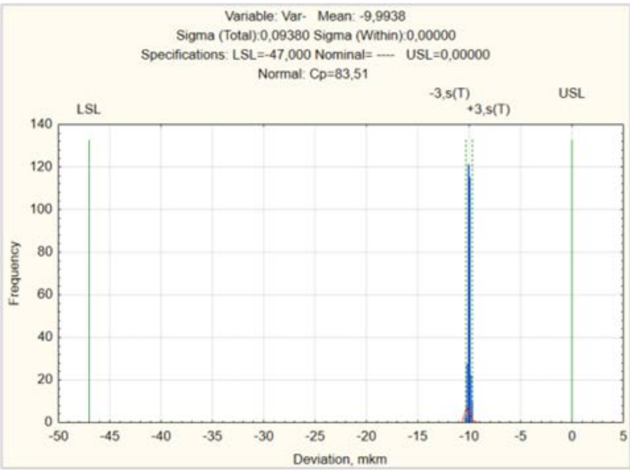
DOI 10.15588/1607-6885-2025-2-10

Where *UAL* and *LAL* are the upper and lower allowable limits of the controlled parameter, respectively; *S* is the standard deviation of the controlled dimension.

Fig. 5a shows the histogram of the controlled diameter deviation distribution, which corresponds to a normal one. Fig. 5b shows the location of the same histogram relative to the tolerance field. For the process under study, the calculated value of PCI is C_P = 83.5.



a



b

Figure 5. Illustration for the PCI analysis:
a – distribution of the controlled diameter; b – distribution of the controlled diameter relatively tolerance field

Discussions

Based on the data analysis, the process was stable during the entire observation period, no special trends such us: the data of 6 consecutive samples are increasing or decreasing, 9 samples on the same side of the center, 14 samples alternating up and down etc. [22] were observed. Based on the results shown in Fig. 4, all the data are within control limits and there are no special trends for the error corrections as well. In combination with the subjection of the corrections to the normal distribution law, it is very likely that positioning error is the subject to exclusively random variations and there are no significant changes in the physical state of the machine tool. The same has been confirmed during scheduled technical inspections.

Thus, there were no fixed deviations in the state of the machine as well as error signals that would indicate that the correction system cannot compensate positioning errors and that repair compensation measures are necessary, which are correlated with the data obtained from the Shewhart charts. Three periodic single outliers of ranges beyond the control limits, observed in Fig. 3, are correlated with the time of technical inspection. Excluding these outliers from the analysed data set results in a pattern where the rest of the data are within the control limits (Fig. 6). This indicates the statistical controllability of the process [22].

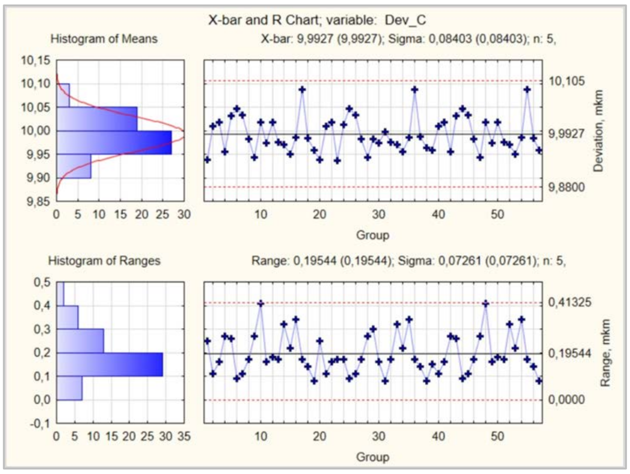


Figure 6. Illustration of the process statistical controllability

The above analysis of the SCC is complemented by that of the deviation distribution, which corresponds to the normal one, indicating that there is no single powerful factor that has a decisive influence on the process results [21]. The calculated value of the PCI - $C_P \gg 10$ indicates that there is no risk of defects and the control process can be simplified. Based on the location of the distribution centre shown in Fig. 5b, an adjustment was made to reduce the hole diameter by 0.012 mm, bringing the average deviation to the middle of the tolerance field.

Based on statistical analysis of the SCC data and the machine positioning error log data at the beginning of the shift and taking into account the fact that no adjustment or repair work is carried out during TI, it is possible to extend the time between inspections by reducing their quantity and performing them when the process begins to acquire characteristics that indicate a possible loss of stability. Skipping the scheduled TI will not cause the machine to lose its operability and will slightly increase the likelihood of failure.

At the same time, the cycle of operations provided under the manufacturer's technological regulations for this type of machine tool, will remain unchanged, and the equipment utilisation rate will increase, which will also reduce the number of repair service personnel. The organisation of this control process requires minimal investment. Data analysis is performed using software that is available at the enterprise and is already used for other processes.

DOI 10.15588/1607-6885-2025-2-10

Based on the results obtained, the production adopted a scheme for organising the repair service of machine tool equipment, shown in Fig. 7. The choice of repair measures is based on the results of statistical process control using the SCC and the corresponding assessment of the equipment condition.

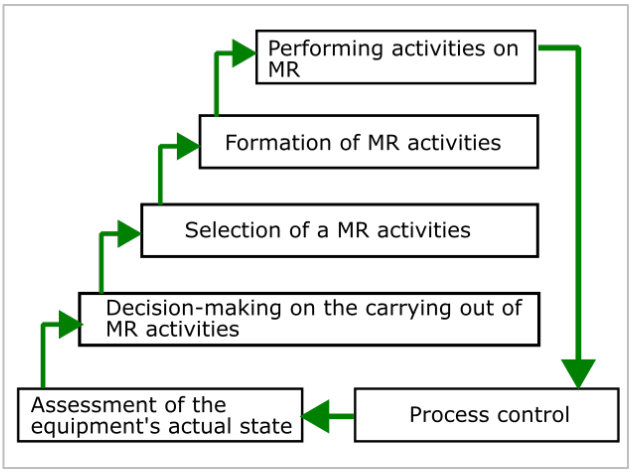


Figure 7. MR model based on the prediction of machine tool performance using Shewhart charts

Conclusions

The monitored characteristics follow a normal Gaussian distribution and it is reasonable to use these data to construct X- and R- Shewhart charts.

The geometric control of the critical dimension and the error correction log data, reflecting the machine positioning error, proposed as a source of data for constructing X- and R- charts, allows monitoring the process state and correlates with the state of the machine.

The frequency of maintenance and repair activities, specified in accordance with the operational regulations does not comply with the actual condition of the machine.

Determining the timing of maintenance operations based on the analysis of statistical data using X- and R- Shewhart charts will not lead to a significant decrease in equipment reliability.

The parallel analysis of the critical size deviation distribution along with the process capability index analysis adequately evaluate the need to reduce or enforce control measures to ensure compliance with the selected quality indicators.

The application of data and software used in parallel production processes does not require significant additional investments when implementing and using the proposed MRO system.

In the subsequent operation of CNC machines using the developed MR model for assessing the actual state of the equipment, the number of repair and maintenance activities was reduced by 35–50 %.

With the accumulation of practical expertise, it is possible to transfer the proposed principles of work to other operations of the repair cycle and to other machines, excluding the mandatory operations specified by the manufacturer for this type of machine.

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Одержано 17.03.2025

ВИКОРИСТАННЯ КОНТРОЛЬНИХ КАРТ ШУХАРТА ДЛЯ ЗАБЕЗПЕЧЕННЯ ЯКОСТІ ПРОДУКЦІЇ ТА ОПТИМІЗАЦІЇ РЕГЛАМЕНТУ ОБСЛУГОВУВАННЯ МЕТАЛОРІЗАЛЬНИХ ВЕРСТАТІВ З ЧПУ. ПРАКТИЧНИЙ ДОСВІД

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Мета роботи. *На прикладі верстата з ЧПУ DAEWOO PUMA 600M, з використанням статистичних методів управління якістю зокрема карт Шухарта, відпрацювати схему технічного обслуговування і ремонту верстатного обладнання з метою скорочення експлуатаційних витрат.*

DOI 10.15588/1607-6885-2025-2-10

Методи дослідження. *Для досліджуваного випадку з кожної партії виробів «Колесо» в 30 од. для п'яти випадкових виробів відділом контролю якості проводився контроль відхилення від номіналу найбільш критичного параметру точності – посадкового діаметру зовнішнього кільця підшипника кочення. Всього було взято 60 таких вибірок. Діаметр посадкового отвору контролювався за допомогою прецизійного триточкового нутроміра. Таким чином для загальної вибірки в 300 одиниць будувалися контрольні карти Шухарта для положення центру і розкиду та здійснювався статистичний аналіз, метою якого є ідентифікація спеціальних трендів. Крім цього, аналогічним чином аналізувалися записи журналу коригувань за якими визначається наявність помилки позиціонування.*

Отримані результати. *Встановлено, що використання контрольних карт Шухарта дозволяє оцінювати фактичний стан верстатного обладнання. Базуючись на цьому факті, запропоновано модель технічного обслуговування і ремонту верстатів з ЧПУ, що спирається на статистичний аналіз даних. Застосування запропонованої моделі до всього циклу обслуговування та ремонтів дозволяє значно подовжити міжремонтні терміни для верстатів з ЧПУ. Кількість ремонтних заходів була зменшена на 35–50%. При цьому циклічність операцій, передбачених технологічним регламентом виробника для даного виду верстатів, залишається без змін, підвищується коефіцієнт використання обладнання та є можливість скоротити необхідну чисельність персоналу ремонтної служби.*

Наукова новизна. *Встановлено зв'язок результатів процесу різання, що встановлюються за контрольними картами Шухарта, та стану обладнання для формування заходів технічного обслуговування і ремонту.*

Практична цінність. *Запропонована схема організації технічного обслуговування та ремонту верстатів з ЧПУ на основі статистичного аналізу з використанням карт Шухарта забезпечує суттєве скорочення витрат на їх експлуатацію.*

Ключові слова: *розкид, контрольні межі, спеціальний тренд, варіація, розподілення, індекс можливостей процесу, фактичний стан обладнання, міжремонтний період.*

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DOI 10.15588/1607-6885-2025-2-10