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Systematic approach to the study of working surfaces wear of automotive and tractor equipment parts

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Abstract

The paper uses the principles of the system approach to establish the relationship between wear of individual surfaces on the example of a gear drive of the GP type pump. The hierarchical structure of the part is considered, its individual functional parts are classified as subsystems, and the working surfaces are classified as system elements. A systematic approach to the study of part wear condition included, in addition to identifying the relationships between the wear of individual elements of the part, the creation of a mathematical statistical model of the worn part as a whole, as a system. The main types of wear of the gear working surfaces were determined. The laws of wear distribution of gear working surfaces and their main numerical characteristics were found. The established relationship between the wear of individual gear elements has become the basis for the system quality of the technical system "gear drive of the GP pump" in relation to the wear of its elements. A mathematical statistical wear model was obtained in the form of linear regression equations system of gear elements wear dependence on their outer diameter wear. This makes it possible, using the principles of a systematic approach based on the data of a single defect – gear wear along the outer diameter, to create a complete statistical image of the worn part, i.e., to determine the wear of other elements of the drive gear. The results obtained allow us to reasonably approach the issue of choosing a method for restoring parts and forming routes for the technological process of restoring a part.

Key words: systematic approach, restoration of parts, wear of the working surface, drive gear, automotive and tractor equipment, mathematical statistical model.

Introduction

The restoration of worn parts remains a very important reserve for increasing the efficiency of equipment use, saving material, fuel and energy, and labor resources. The technical and economic feasibility of restoring parts is due to the possibility of reusing 65-75% of the parts (often repeatedly). The cost of restoring worn parts does not exceed 50% of the cost of new ones, and material costs are 15-20 times lower than during the manufacture of parts [1].

At the same time, the problem of restoring parts is complex in nature [2]. To study and solve it, it is possible to apply a systematic approach, which is a methodological orientation of study based on the consideration of objects in the form of systems, that is, a set of elements connected by interaction, and therefore acting as a single whole in relation to the environment [3].

The choice of optimal restoration methods and their sequence is determined by many factors and in many cases is associated with increasing hardness, achieving a set of mechanical properties, wear resistance, as well as the roughness of the restored surface and the dimensional accuracy of the restored part [4].

Each restoration method has its own niche of optimal conditions of use, including even the technological traditions that have developed at a particular enterprise, so the implementation of a systematic approach to the restoration of parts, in particular, vehicles, is a decisive factor in the selection of primary processing methods in the technological restoration process and the possibility of integrating them into a single technological cycle [5].

Literature review

The technological process of restoring machine parts, including automotive and tractor equipment, has all the necessary properties that are required for systems [1, 3, 4]:

- is an integral complex of interconnected elements, such as parts, technological operations, modes, etc;
- is an element of a higher-order system, in particular, the production process of machine repair;
- technological process elements can be considered as lower-order systems (a technological operation consists of the following interconnected elements: equipment, fixtures, tools, part, transition).

It should be noted that a part as an object of design or restoration also corresponds to all the above system concepts [6]. Possessing integrity, it consists of interconnected parts, functional and structural components depend on the type and complexity of the part design, its purpose. Considering a part as a system, it can be divided into subsystems or only into elements. In a part-system, one of the subsystems (or one of the elements) is the main one, its role in determining the state of the entire system is more significant than the influence of other subsystems. The main elements of a part are the mating surfaces.

As an example, consider the hierarchical structure of the drive gear of hydraulic pumps (Figs. 1, 2), which are widely used in hydraulic systems of automotive and tractor equipment.

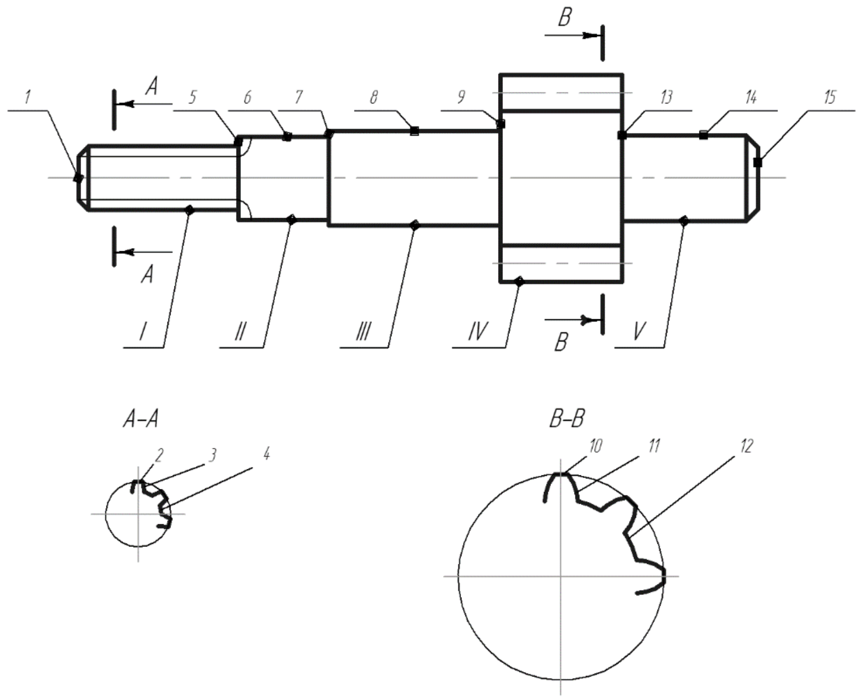

Fig. 1. Structure of the part design: I-V – functional parts of the part; 1-15 – surfaces of the part

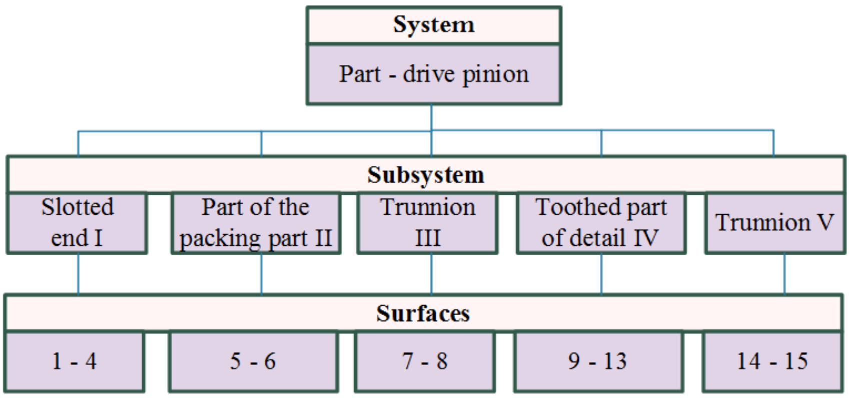

Fig. 2. Scheme of the hierarchical structure of the part

In such a system, one of the subsystems is the main one, and its role in determining the state of the entire system is more significant than the influence of other subsystems. The main elements of a part are the mating surfaces.

As a rule, there are no more than six types of defects in a part [7]. However, combinations of two, three, and sometimes four defects are most common. The probability of *n* defects occurrence out of *m* possible in worn parts can be determined using a binomial distribution:

$$P_m(n) = C_m^n P^m q^{m-n}, \quad (1)$$

where C_m^n – the number of n defect combinations out of m possible; P – the probability of defect occurrence; q – the probability of defects occurrence.

The connection between individual surfaces can be functional and correlative.

The functional connection feature allows classifying defects and their combinations into separate classes by combining such defects into common restoration routes.

Usually, when studying the wear of a part, the wear of each element of the part is considered separately. The wear of one surface (element) of the part is not related to the wear of other surfaces. A systematic approach to studying the wear state of a part involves studying and finding relationships between the wear of individual elements of the part, i.e. creating a mathematical statistical model of the worn part as a whole, as a system.

Purpose

The aim of this paper is to use a systematic approach to construct a mathematical statistical model of a worn part that will establish the relationship between the wear of individual surfaces on the example of a gear drive of the GP type pump.

Research Methodology

A static mathematical model of a worn part will be understood as a mathematical image of a part whose characteristics that determine the type, degree, and relationship of wear are adequate to the real picture.

The construction of the mathematical model of the worn gear was as follows:

1. Collecting information about the wear of pump gears by micrometering.
2. Determining the minimum required sample size.
3. Determining the numerical characteristics of a random sample:

average wear value; absolute scattering index – dispersion and average square deviation and relative scattering index – coefficient of variation.

4. Checking the collected information for dropout points.
5. Selecting a theoretical distribution law and determining its parameters.
6. Using a systematic approach to creating a mathematical image of a worn part, the characteristics of which determine the type, degree and relationship of wear, are adequate to the real picture. This involves determining the pairwise correlation coefficients, creating regression equations for the relationship between the wear of individual elements of the part, checking the coefficients of the resulting regression equations for significance, and the entire regression equation for adequacy.

The main defects of the GP pump drive gear are shown in Fig. 3.

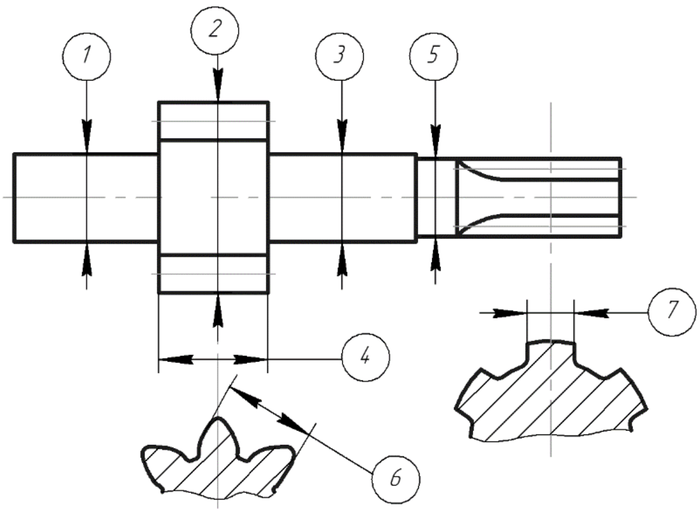

Fig. 3. Defects of the drive gear of the GP-46U pump: 1,3 – wear of the trunnion diameter; 2 – wear of the gear outer diameter; 4 – wear of the width of the gear crown; 5 – wear of the neck diameter under the oil seal; 6 – wear of the general normal of the gear teeth; 7 – wear of the drive gear splines in width

The measuring tool for determining the amount of wear was chosen based on the accuracy of the dimensions in the manufacture of gears and the amount of wear on its working surfaces.

A micrometer MK-50-1 DSTU GOST 6507:2009 Micrometers was used to determine the wear of the trunnion and neck for the oil seal by diameter, as well as the gear by tooth length. Technical specifications (GOST 6507-90) with a division price of 0.01 mm.

The spline thickness wear was determined by a vernier caliper SHTS-II-250-0.05 DSTU GOST 166:2009 Vernier calipers. Technical specifications (GOST 166-89 (ISO 3599-76), IDT) with a division price of 0.05 mm.

To determine the wear of the gear teeth along the involute profile, the length of the general normal was measured with a micrometer M3-25-I according to DSTU GOST 6507:2009 Micrometers. Technical specifications (GOST 6507-90) with a division price of 0.01 mm.

Statistical processing method of the obtained experimental data on the wear of the drive gear of the GP type pump as a system was performed according to the recommendations given in paper [8].

Statistical processing of information on the wear of gear elements was performed in accordance with the recommendations using the Statistica software [9].

The systematic approach to building a statistical mathematical image (model) of a worn part, in addition to the laws of part wear distribution, involves determining the relationship between the wear of the part's working surfaces.

The presence and closeness of the relationship between the wear of gear elements, i.e., the qualitative side of the issue, is determined by correlation analysis methods.

The stochastic relationship between the wear of gear working surfaces is determined by regression analysis methods. The method allows determining how the resultant attribute changes quantitatively when the factor attribute changes.

When obtaining regression equations for the relationship between the wear of gear elements, the wear of gears along the outer diameter was chosen as an independent factor. This is due to the fact that:

- first, it is the wear of the gears on the outer diameter that largely determines the volume flow rate of the pump;
- secondly, due to the uniform wear of the gears along the outer diameter, the determination of wear of this element is technologically advanced and accurate;
- thirdly, the wear of other gear elements also depends on the wear of the gears along the outer diameter.

The experimental information on gear wear was processed by regression and correlation analysis according to the method given in paper [10].

Results

It was found that abrasive wear is the predominant type of wear on the gear working surfaces. This is evidenced by the characteristic marks on the wearing surfaces (Fig. 4, a-c). Wear of the involute tooth profile should be attributed to mechanical abrasion (Fig. 4, d).

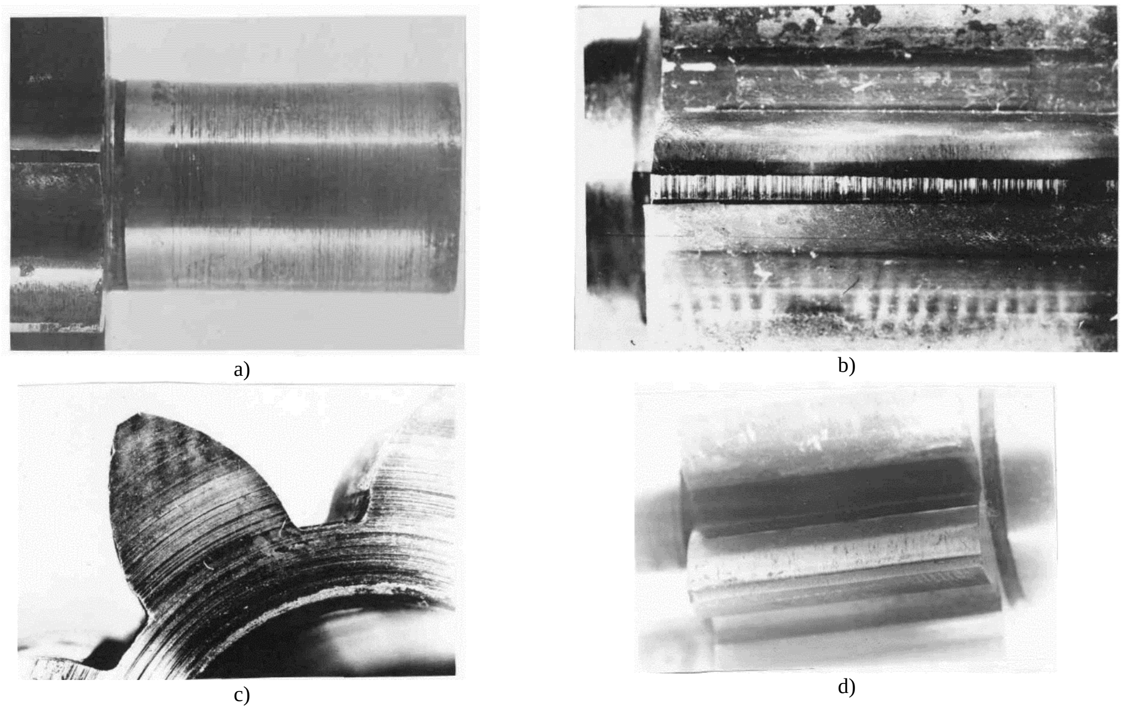

Fig. 4. Traces of abrasive wear on the surfaces of the gear trunnion (a), gear tooth tip (b), gear face (c), and mechanical abrasion of the tooth head (d)

The information on the wear of gear elements was processed in accordance with the methodology [11]. The main characteristics of the wear distributions of GP pump gears are shown in Table 1.

Table 1

Main characteristics of wear distribution on gear working surfaces of pumps GP-46U

Name of the distribution parameters	Pumps that came in for repair for the first time		Pumps that came in for repair for the 2nd and 3rd time	
Wear of gears on the outer diameter, ΔD_i				
Average amount of wear, $\bar{t}$	0.091	0.074	0.348	0.315
Average square deviation, σ	0.088	0.092	0.215	0.196
Asymmetry, A	1.141	2.53	0.369	0.056
Excess, E	1.376	9.45	0.274	-0.769
Coefficient of variation, V	0.967	1.23	0.619	0.624
The law of distribution	Laplace-Charlier	normal	Laplace-Charlier	normal
Probability of acceptance the hypothesis, P	0.85	0.19	0.995	0.975
Wear of the gear trunnions in diameter, $\Delta d_{цi}$				
Average amount of wear, $\bar{t}$	0.026	0.018	0,248	0,224
Average square deviation, σ	0.024	0.032	0.116	0.107
Asymmetry, A	1.120	3.59	-0.284	-0.238
Excess, E	1.36	16.13	-0.897	-1.02
Coefficient of variation, V	0.94	1.75	0.467	0.476
The law of distribution	Laplace-Charlier	Uniform	Laplace-Charlier	Laplace-Charlier
Probability of acceptance the hypothesis, P	0.81	0.86	0.927	0.944
Gear wear along the tooth width, Δb_i				
Average amount of wear, $\bar{t}$	0.147	0.106	0.576	0.595
Average square deviation, σ	0.142	0.155	0.273	0.314
Asymmetry, A	1.04	2.7	0.45	0.303
Excess, E	0.532	9.4	0.74	-0.041
Coefficient of variation, V	0.968	1.46	0.474	0.53
The law of distribution	Laplace-Charlier	normal	normal	Laplace-Charlier
Probability of acceptance the hypothesis, P	0.617	0.544	0.997	0.99
Wear of gear teeth along an involute profile, ΔW_i				
Average amount of wear, $\bar{t}$	0.011	0.01	0.028	0.031
Average square deviation, σ	0.033	0.026	0.064	0.065
Asymmetry, A	3.9	3.49	2.84	2.55
Excess, E	16,2	13.23	7.77	7.62
Coefficient of variation, V	2.96	2.65	2.32	1.79
The law of distribution	Uniform	Uniform	Uniform	Uniform
Probability of acceptance the hypothesis, P	0.437	0.37	0.12	0.07
Error in gear tooth direction, F_β				
Average amount of wear, $\bar{t}$	-	-	0.077	0.071
Average square deviation, σ	-	-	0.022	0.020
Coefficient of variation, V	-	-	0.285	0.280

Analyzing the results of statistical processing of the working elements of the GP pump drive gear, we come to the following conclusions. The overwhelming majority of gear element wear distributions obey either the normal law or the Laplace-Charlier distribution law (the latter law is obeyed by random variables close to the normal distribution, but having an asymmetry and excess other than zero). And as is known, the wear phenomena are based on a normal distribution law. This indicates the correct approach to solving the problem. The asymmetry and excessiveness of the wear distribution indicators, which determined the discrepancy between the actual distribution and the normal distribution, are usually small and can be attributed to random events.

The results of constructing a statistical model of a worn gear (Table 2) make it possible to establish the relationship between the wear of gear elements.

The obtained dependencies (2) ... (5) are shown graphically in Fig. 5. From the analysis of the obtained regression equations, it follows that there is a linear relationship between the wear of gear elements (see Fig. 5). In all the dependencies, with the growth of the factorial feature – ΔD_{ei} , the effective feature also grows. This suggests that with an increase in wear of one of the surfaces, wear of other working surfaces of the gears also increases.

Table 2

Results of constructing a statistical model of a worn gear

Variable	Average value, $\bar{t}$	Average square deviation, σ	Coefficient of variation, V	Student's t-test, $t_ф$ at α=0.99	Regression equation $y = ax + b$
Independent variable Wear of gears by outside diameter – ΔD_{ei}	0.47	0.176	-	-	-
Dependent variables Wear of gear trunnions by diameter – $\Delta d_{шi}$	0.30	0.27	0.809	$t_ф$=6.74 t_α=2.79	$\Delta d_{шi} = 0,755\Delta D_{ei} - 0,052$ (2)
Wear of gear teeth by width – Δb_i	0.52	0.23	0.738	$t_ф$=5.36 t_α=2.79	$\Delta b_i = 0,98\Delta D_{ei} + 0,059$ (3)
Wear of gears on involute profile – ΔW	0.058	0.021	0.751	$t_ф$=5.59 t_α=2.79	$\Delta W_i = 0,090\Delta D_{ei} + 0,016$ (4)
The gear tooth direction error – F_β	0.064	0.035	0.96	$t_ф$=18.7 t_α=2.79	$F_\beta = 0,195\Delta D_{ei} - 0,027$ (5)

As shown by the calculations for the correlation and regression coefficients of all relations (2) ... (5), the following condition $t_ф = r_{xy}\sqrt{n-1} > t_\alpha^*$ is fulfilled, which indicates their significance. In addition, condition $F_{роз} > F_\alpha^*$ is fulfilled for all regression equations, which indicates the adequacy of the obtained dependencies.

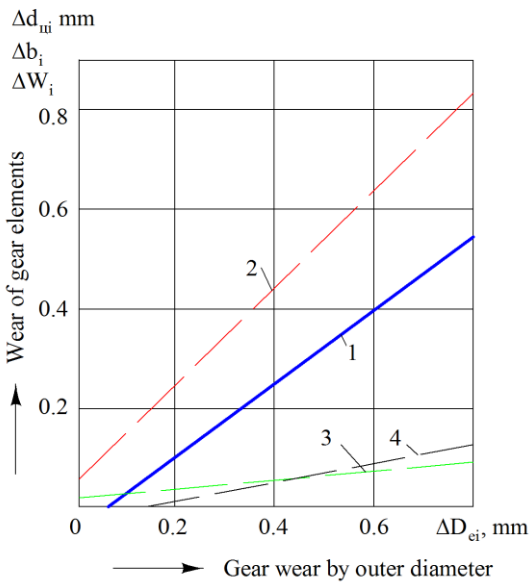

Fig. 5. Graphical display of linear regression equations:

1 – Graph of the regression equation for the wear of the gear width on the wear of the gear by the outer diameter $\Delta b_i = 0,98\Delta D_{ei} + 0,059$ (3); 2 – Graph of the regression equation for the wear of the gear trunnions on the wear of the gear by the outer diameter $\Delta d_{шi} = 0,755\Delta D_{ei} - 0,052$ (2); 3 – Graph of the regression equation for the error of tooth alignment on the wear of the gear by the outer diameter $\Delta W = 0,195\Delta D_{ei} - 0,027$ (4); 4 – Graph of the regression equation for the wear of gears along the involute profile on the wear of the gear by the outer diameter $F_\beta = 0,195\Delta D_{ei} - 0,027$ (5)

Thus, the presented results indicate the existence of an unambiguous correlation relationship between gear surface wear.

The obtained equations (2) ... (5) make it possible to determine the wear of each of the working surfaces, knowing the wear of the gears along the outer diameter – ΔD_{ei} with a confidence level $\alpha = 0,99$. In addition, the equations of the relationship between the wear of gear elements make it possible to create a mathematical image of a worn gear and implement it according to the developed methodology.

Conclusions

Obtained results allowed drawing the following conclusions:

1. The considered part – the drive gear of hydraulic pumps in the form of a system consisting of interconnected parts, its structural parts can be considered as subsystems, and the surfaces, in turn, are elements of the system.

2. It is shown that the predominant type of wear on the working surfaces of gears is abrasive wear. Wear of the involute profile of the gear teeth and splines should be attributed to mechanical abrasion.

3. The distribution laws of wear on the working surfaces of gears and their main numerical characteristics are found. The distribution of gear wear obeys mainly the normal distribution law and also the Laplace-Charlier law.

4. The relationship between the wear of individual surfaces (elements) of the gear was revealed, which became the basis for the presence of system quality (emergence) of the technical system "gear drive of the GP pump", relative to the wear of its elements.

5. The emergence of the technical system "gear drive of the GP pump" made it possible to create a mathematical statistical model, an image of a worn part in the form of linear regression equations system of wear dependence of gear elements on their outer diameter wear. This makes it possible to create a holistic statistical image of the worn part based on a systematic approach to determining one defect, in this case, gear wear along the outer diameter, i.e. to determine the wear of other elements of the part.

6. The resulting mathematical statistical model of a worn part becomes the basis for a systematic approach to justifying the choice of a method for restoring parts and forming routes for the technological process of restoring a part.

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Черновол М.І., Кропівний В.М., Кулєшков Ю.В., Шепеленко І.В., Гуцул В.І. Системний підхід при дослідженні зносів робочих поверхонь деталей автотракторної техніки

Використовуючи принципи системного підходу встановлено взаємозв’язок між зносами окремих поверхонь на прикладі ведучої шестерні насоса типу НШ. Розглянуто ієрархічну структуру деталі, її окремі функціональні частини віднесені до підсистем, а робочі поверхні – до елементів системи. Системний підхід до вивчення зносного стану деталі передбачав, крім виявлення взаємозв’язків між зносами окремих елементів деталі, створення математичної статистичної моделі зношеної деталі як однієї цілої, як системи. Визначені ведучи види зношування робочих поверхонь шестерні. Знайдено закони розподілу зносів робочих поверхонь шестерні та основні числові їх характеристики. Встановлений взаємозв’язок між зносами окремих елементами шестерні став основою наявності системної якості технічної системи «шестерня ведуча насоса НШ» відносно зносів її елементів. Отримана математична статистична модель зношеної деталі у вигляді системи лінійних рівнянь регресії залежності зносів елементів шестерень від зносу їх по зовнішньому діаметру. Це дозволяє використовуючи принципи системного підходу, за даними одного дефекту – зносу шестерень по зовнішньому діаметру, створити цілісний статистичний образ зношеної деталі, тобто визначити зноси інших елементів ведучої шестерні. Отриманні результати дозволяють обґрунтовано підійти до питання вибору способу відновлення деталей та формування маршрутів технологічного процесу відновлення деталі.

Ключові слова: системний підхід, відновлення деталей, знос робочої поверхні, ведуча шестерня, автотракторна техніка, математична статистична модель