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Chapter

Technological Control on the Heredity of Operational Quality Parameters

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Abstract

Technological heredity of operational properties in the processes of manufacturing, operation, and restoration of machine parts is proposed to describe the graph reflecting the coefficients of transmission and mutual influence of physical, mechanical, and geometric parameters. The technological control methods of the heredity of operational properties of parts are considered, including the following: measuring parameters of the most critical parts; determining technological heredity mechanisms on the basis of transfer coefficients and mutual influence of operational properties; analyzing technological barriers during intensive effects of energy flows; and developing measures for controlling technological processes. The technological heredity of the operational quality parameters in the process of recovery and processing of the bearing journals and cams, as well as wearing of the camshaft working surfaces over admissible limits are considered. According to the findings, it is recommended: to control the deformation of the part after machining operations; to eliminate the editing operation after heat treatment; to use a combination of methods and a combination of technological effects in recovering the part surfaces with wear exceeding the maximum permissible values. The need for surfacing and subsequent tempering processes to ensure consistently high physicomechanical properties of coating materials and strictly regulate the modes of surface finishing is noted.

Keywords: technological heredity, operational properties, processed material, part surfaces, physicomechanical and geometric quality parameters, wear limit, engine camshaft, surfacing recovery, bearing journals, cams, mechanical treatment, internal combustion engine, crankshaft, camshaft

1. Introduction

The heredity in engineering technology is understood as the phenomenon of transferring the properties of the processed object from previous operations and transitions to the next ones, which further affects the operational properties of machine parts [1, 2]. The carriers of heredity information are the processed material and the part surfaces with all the variety of parameters describing them. Information carriers are actively involved in the technological process and in operation, going through various modes and transitions, experiencing the effects of technological factors [3, 4].

In the technological chain and at the stage of operation, there are some kinds of "barriers." Some technological factors cannot overcome them, and in this case, they do not affect the final properties of the object. Other factors pass through such "barriers," but their influence on the final properties significantly decreases [1, 3]. The most significant "barrier" is thermal operations, as well as operations accompanied by surface deformation and hardening, as they change the microstructure of the processed material and the microgeometry of the formed surface, leading to the deformation of the part and distortion of its shape. During these operations, various surface defects, such as structural heterogeneity, pores, and microcracks, can develop or heal. Consequently, it is possible to control the process of technological and operational heredity so that properties that positively affect the quality of the part are maintained throughout the entire technological process, while properties that affect negatively are eliminated at the beginning of the process [4, 5].

A distinctive feature of existing approaches to the definition and prediction of quality indicators for engineering products is the use of the superposition principle, according to which each of the existing technological factors is independent of the others, and the result of joint action is determined by their partial sum represented in one form or another [3, 4].

However, the technological systems are multiply connected, and the production objects are characterized by nonlinearity, irreversibility, and disequilibrium. The application of the superposition principle reduces the multiply connected interactions, which take place in the technological systems, to simply connected interactions, ignoring the mutual influence of technological factors [4, 5].

With the growth of requirements for the quality of machining parts' surfaces, methods for determining and predicting quality based on the principle of superposition become of little use, since the effect of the mutual influence of factors is comparable with the results of their direct impact. The process of ensuring the product properties should be considered as a set of interacting processes, changing and preserving the properties [6, 7].

In the repair industry, the transfer of physicomechanical and geometric quality parameters when performing various machining, welding, surfacing, heat treatment, surface hardening, and other operations determines the structure of the material and the surface layer of the part [2, 6, 7]. Therefore, the negative effects associated with the technological heredity should be taken into account when forming the technological process [1, 2, 7].

2. The synergetic concept of the state of a thermodynamic system

It is reasonable to determine the dominant processes of structure formation under intense effects in terms of synergetics using the concept of a mode in the distributions of continuous random variable of controlled parameter [8].

By a mode, we mean such a value of the parameter at which the density of its distribution is at a maximum. According to the synergetic concept, stable modes adjust to the dominant unstable modes and consequently can be excluded. This leads to a drastic reduction in the number of controlled parameters—degrees of freedom of a thermodynamic system. The remaining unstable modes can serve as the parameters of order that determines the processes of structure formation [9].

The equations of state of the thermodynamic systems, resulting from the reduction of the parameters, are grouped into several universal classes of the form [8, 9]:

$$\frac{\partial}{\partial \tau} U = G(U, \nabla U) + D \nabla^2 U + F(\tau), \tag{1}$$

where U—a controlled parameter; τ—current time; G—a nonlinear function of U and may be U gradient; D—the coefficient that describes either the diffusion when its value is real or the propagation of waves when its value is imaginary; and F—fluctuating forces due to the interaction with the environment and dissipation inside the system.

Equations of this type are similar to the equations describing phase transitions of the first and second kind. In accordance with the synergetic concept, phase transitions occur as a result of self-organization, a process which is described by three degrees of freedom, corresponding to the order parameter (O), its conjugate field (F), and control (C) parameter [9].

To use a single degree of freedom—the order parameter—is possible only for describing the quasi-static phase transformation. In the systems which are far from being in thermodynamic equilibrium, each of these degrees of freedom acquires an independent significance.

The processes of self-organization in them result from the competition of the positive feedback of the order parameter with the control parameter and the negative feedback with the conjugate field. Consequently, except for the process of relaxation, at the equilibrium state over time τ^p with two degrees of freedom, a self-oscillating mode can be realized, and with three degrees, a transition into a chaotic state can take place [8, 9].

Thus, the state of thermodynamic systems under intense treatment and operation is characterized by a number of modes [10, 11]:

1. *memorizing*—it is determined by a "frozen" disorder in the transition from a disordered state and is implemented when the time of the order parameter relaxation is much smaller than any other time ($\tau^p_O << \tau^p_C$ and $\tau^p_O << \tau^p_F$);

2. *relaxation*—it is realized when the time of relaxation of the order parameter is much greater than the relaxation time of the remaining degrees of freedom ($\tau^p_O >> \tau^p_C$ or $\tau^p_O >> \tau^p_F$);

3. *self-oscillation*—it requires the commensurability of the characteristic time of a change in the order parameter and the control parameter or the conjugate field ($\tau^{p\ >}_{O<}\ \tau^p_C$ or $\tau^{p\ >}_{O<}\ \tau^p_F$); and

4. *stochastic*—it is characterized by a strange attractor and is possible if all of the three degrees of freedom are commensurable ($\tau^{p\ >}_{C<}\ \tau^{p\ >}_{O<}\ \tau^p_F$).

The dominating processes of structure formation are determined by the intensity of energy and matter transfer in nonequilibrium thermodynamic systems. The stability of structure formation is provided by the control of the stability of the processes of intensive processing and operation through the use of positive and negative feedbacks [10, 11].

2.1 Thermal treatment of metals and surfaces

The purpose of any thermal treatment processes is to provide a desired material structure by heating (or cooling) it up to a certain temperature and subsequently changing it [12]. The mode of thermal treatment is typically characterized by the following basic parameters: the temperature of heating and holding time and the speed of heating and cooling of the material [13].

All the types of thermal treatment, according to Bochvar [14], are divided into four main groups of operations, which in terms of the synergetic concept of structure formation can be associated with the modes of the thermodynamic system behavior.

The modes are defined by relaxation times τ^p, which refer to (i) the order parameter at cooling, (ii) the structure formation parameter conjugated with the previous one, and (iii) the control parameter for thermal treatment, namely heating. The presence of two degrees of freedom determines a thermal cycle, while three degrees of freedom denote a cycle with phase transitions.

As a result, groups of operations of thermal treatment are implemented [13, 14]:

1. *hardening*—heating above the transformation temperature followed by apid cooling to obtain a structurally unstable state;

2. *tempering*—heating of the hardened material below the transformation temperature followed by cooling to obtain a more stable structural state;

3. *annealing of the first kind*—heating the material in an unstable state after the pretreatment followed by slow cooling, resulting in a more stable structural state; and

4. *annealing of the second kind*—heating above the transformation temperature followed by slow cooling to obtain a structurally stable state.

2.2 Plastic deformation and metal forming

Phase transformations used in thermal treatment are primarily caused by a change in temperature, but varying the other thermodynamic factor—the pressure—it is possible to obtain structural changes that do not occur at constant pressure [12, 13].

According to the synergetic concept of structure formation, types of materials forming, like the types of thermal treatment, can be divided into four main groups of operations related to the modes of behavior of a thermodynamic system [8, 11].

Forming modes are also determined by time τ^p: of the order parameter during relaxation (stress relieving), structure formation parameter conjugate with it, and the parameter of mechanical processing control—pressure. Two degrees of freedom determine cyclic hardening, and three—stochastic cold hardening and destruction.

Hence, the following metal forming processes corresponding to different sections of the generalized curve "strain-stress" are [8, 11]:

1. *impact*—local or uniform pressure to form a state of stress and deformation structures or destruction;

2. *stress relaxation*—no pressure after preloading accompanied by the removal of internal stresses and formation of more equilibrium structures;

3. *cyclic cold hardening*—the creation of hardening deformation structures by cyclic formation of the stress state as a result of the application and removal of the load; and

4. *stochastic cold hardening*—the creation of hardening deformation structures by aperiodic formation of stress state as a result of stochastic loading.

3. Quality indicators of machine parts surfaces

The quality indicators of engineering products, which are the main ones, are divided into two categories [15, 16]: the first category includes those that are

characterized by heredity phenomena related to the properties of product materials; and the second category comprises the quality indicators related to the geometrical parameters of their surfaces.

Indicators of both categories in multiply connected technological and operational environments mutually influence each other. Geometrical product parameters, such as product configurations and sizes, can influence the stresses distributed in the base material and surface layers. On the contrary, the stresses generated during the technological hardening process and operation stages may, over time, lead to changes in the geometrical parameters of the parts. This testifies to the interconnection and conditionality of the phenomena accompanying the technological and operational processes.

The most complete heredity of the main quality indicators is revealed when considering the sequence of processes from the synergistic positions of the joint action of technological factors with the mutual influence of indicators [10, 11].

The initial quality indicators for machine parts at various scale levels (**Figure 1**) vary during operation [7, 10]. The exceptions are the residual stresses and the structure of the base material, which can be maintained until the rubbing surfaces of the parts are completely destroyed. In most cases, already during the period of running-in, the roughness and structure of the surface relief significantly change. The waviness and structure of the surface layers of the part change with steady wear, and the geometric shape of the friction surface remains within the allowable values adopted during manufacture almost to the end of the friction unit service, if its performance is assessed by accuracy parameters [2, 5, 7].

Reducing the sensitivity of technological and operational environments to the changes in the conditions for the implementation of production modes and the use of products allows to carry out the directional formation of quality indicators in the life cycle of engineering products for the least cost [2, 16]. The functional models of multiply connected technological environments allow, depending on the

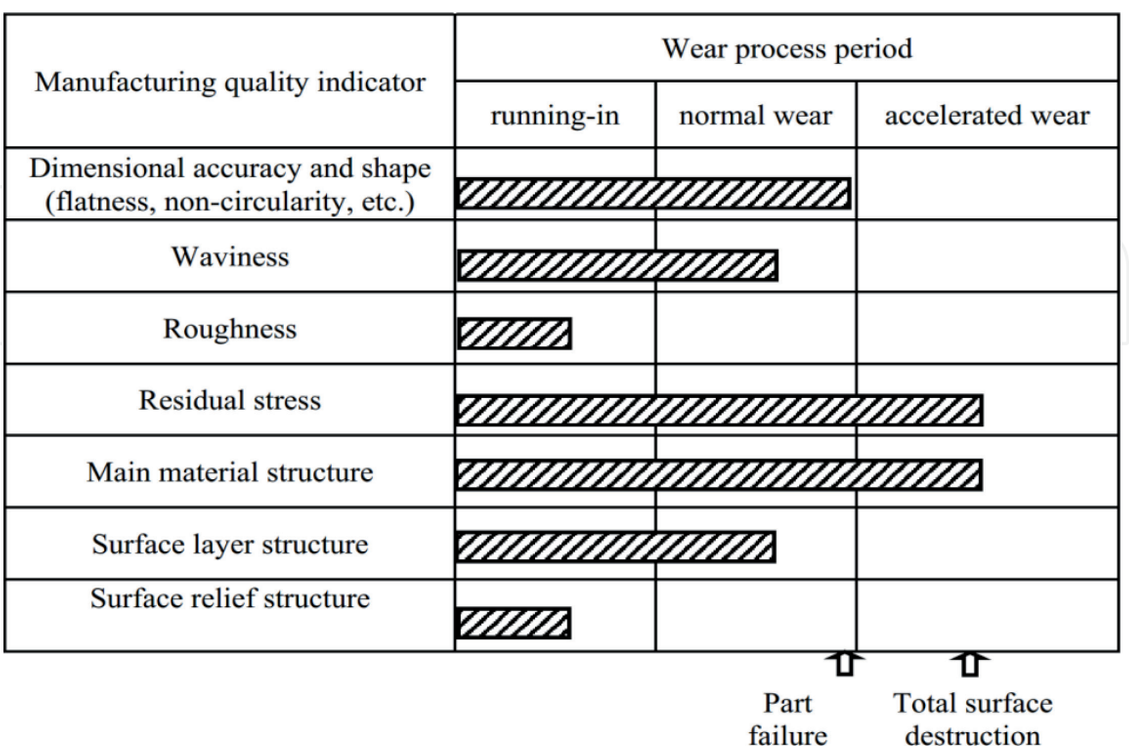


Figure 1.
Diagram of changes in initial quality indicators of product surface during operation (shaded areas characterize the duration of preservation of the initial values in the geometric parameters, residual stresses, and the material structure within permissible deviations).

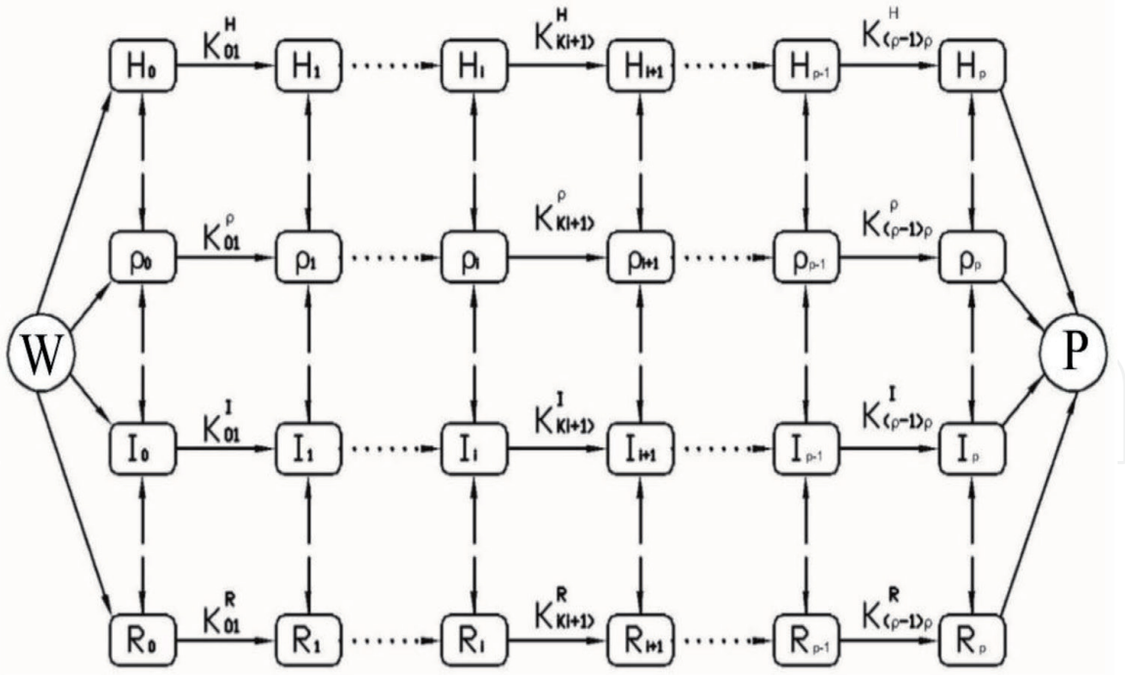


Figure 2.
A detailed graph of technological and operational heredity with a set of quality indicators.

formulation of the problem being solved, to reduce its dimension by highlighting a number of essential connections and suppressing insignificant connections while maintaining correctness and adequacy [6, 11].

3.1 The structure of the relationship of inherited properties

The technological process of manufacturing and operating parts can be represented as a graph, highlighting the procurement, draft operations, finishing operations, as well as performance stages [7].

The graph, as a rule, is oriented, and the quality parameters are interconnected (**Figure 2**).

The initial vertex of the graph, when describing the technological process, is a workpiece W, the final vertex is the finished part P in operation. Oriented edges of the graph show the transfer of operational properties of the part during processing.

The edge transfer is described by the heredity coefficient K, reflecting a quantitative change in the property and equal to the ratio of the previous S_j and subsequent S_{j+1} property values [4]:

$$K = S_j / S_{j+1} \tag{2}$$

In addition to the direct transfer of properties (**Figure 2**) with technological and operational heredity, it is advisable to evaluate their interaction (**Figure 3**).

3.2 Main inherited quality indicators

To identify the main quality indicators inherited in operation, through the control of which it is advisable to manage the technological process, the ABC analysis was performed (**Figure 4**), highlighting the reasons for the change in the initial geometric parameters of the surface and the physicomechanical characteristics of the material during operation [5].

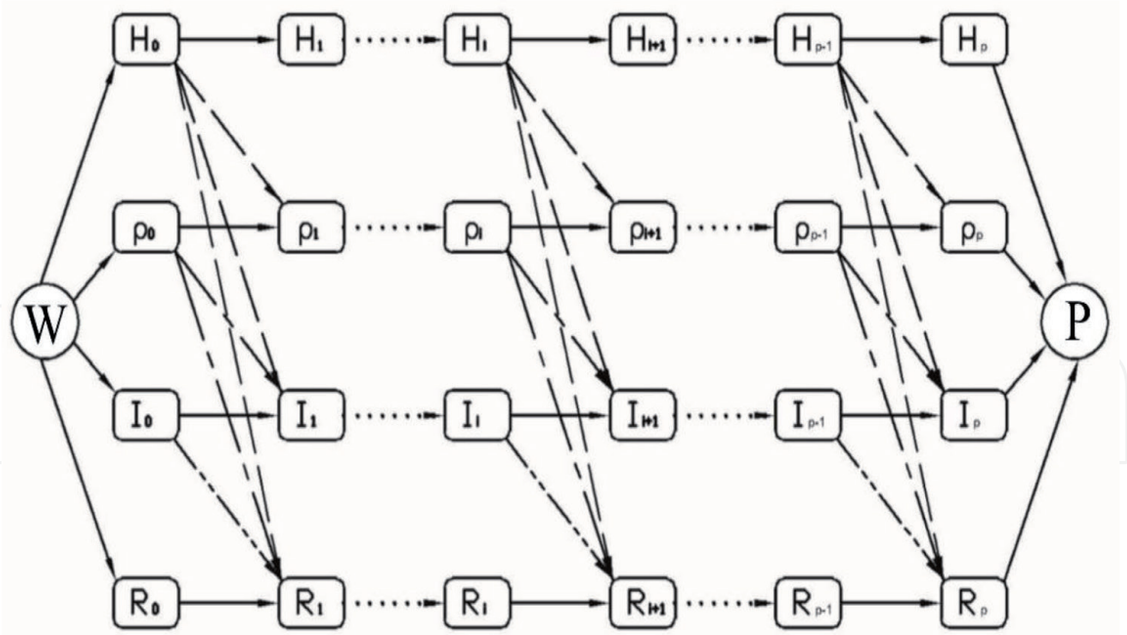


Figure 3.
The graph of technological and operational heredity reflecting the mutual influence of physicomechanical and geometric quality indicators.

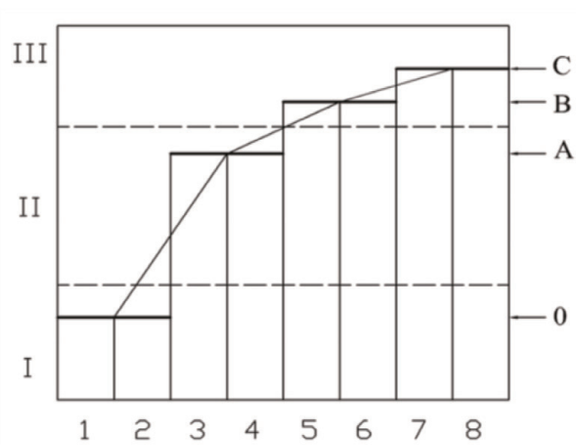


Figure 4.
ABC analysis of changes in operation process (I–II) of initial quality indicators (1–8): 0—the surface formation; A—the change in contact loads; B—part failure; C—complete destruction of the surface; I—running-in; II—normal wear; III—catastrophic wear; 1—the surface roughness; 2—the surface relief structure; 3—the surface waviness; 4—the structure of the surface layers; 5—the surface shape; 6—the dimensional accuracy; 7—residual stresses; and 8—the structure of the main material.

The ABC analysis showed that in most cases, already during the running-in period (I), the roughness (1) and the surface relief structure (2) change significantly. The waviness (3) and the structure of the surface layers (4) change with steady wear (II). The accuracy of dimensions (5) and the geometric shape of the surface (6) remain within acceptable limits even at the beginning of the catastrophic wear stage (III). Only residual stresses (7) and the structure of the main material (8) can be maintained until the rubbing surfaces are completely destroyed [7].

Therefore, to study the heredity, we selected the operatively and least laboriously controlled physicomechanical geometric quality indicators from the initial and final groups (0–C). At the same time, special attention was paid to indicators (5, 6) undergoing significant changes at the beginning of catastrophic wear (B) and related both to the physicomechanical characteristics of the material (7, 8) and to the geometric parameters of the surface relief (1, 3).

3.3 Methods of research

The study and management of the technological and operational heredity by the proposed method of quality parameters control was carried out for the parts responsible for the product life [10, 17].

Measurements of hardness HRC, shape deviations ρ, dimensional accuracy *IT*, and surface relief *Ra* were carried out on a batch of parts. It was divided into 10 groups, and the arithmetic average of the group was taken as the calculated value.

On the basis of the calculated results, the heredity transfer coefficients K^{H}, K^{ρ}, K^{I}, and K^{R} were determined for the graph in **Figure 6**, and the coefficients of the technological effect heredity $K^{H\rho}$, K^{HI}, K^{HR}, $K^{\rho I}$, $K^{\rho R}$, and K^{IR} were done for the graph in **Figure 3**.

To assess the heredity of the technological route, the resulting coefficients K_r were calculated, equal to the product of the corresponding coefficients for the operational quality parameters throughout the entire sequence of operations. To determine the degree of heredity influence on various technological operations, the comparison coefficients K_c, equal to the ratio of mutual influence coefficients on the previous and subsequent operations, were calculated [18].

4. The heredity quality parameters by recovering

The technological process of recovery and hardening of the camshaft can be divided into the stages of flaw detection; shape recovery and hardening; final surface treatment; running on the stand; and further operation. In this regard, the study of all quality parameters was carried out not after each individual operation, but after the selected stages.

The parameters were measured on the surfaces of the bearing journals and cams since these surfaces are friction surfaces and are constantly in contact with other surfaces. On the surface of the bearing journals, friction forces are constantly acting, and the cams undergo cyclic loading [2, 7].

The measurement results were entered into the tables in which the data on the number of each journal or cam are vertically arranged, and the data on the classes are presented horizontally. The data were designed in such a way that it was possible to analyze not only the measurement results of different classes of parts, but also the differences in the data for different numbers of journals and cams throughout the entire length of the shaft. On the basis of the tabular data, the graphs were built (**Figures 5–11**) showing the changes in the quality parameters for selected stages of the technological process of recovering the UMZ-4173 engine camshaft. The graphs analyzed the processes of changing the operational quality parameters and found their patterns.

According to the experimental data, the transfer coefficients of the technological heredity, equal to the ratio of individual quality parameters before and after the operation, and the mutual influence coefficients of various quality parameters during processing and operation were calculated. The calculations were carried out for bearing journals (no. 1–5) and cams (no. 1–16) in classes (no. 1–10) allocated (stratified) depending on the wear degree of the working surfaces of the UMZ-4173 engine camshafts (**Tables 1–4**).

In experimental studies of the operational parameters of the UMZ-4173 engine camshaft, the hardness of the material was taken as the main physicomechanical parameter. The radial runout, dimensional accuracy, and surface roughness were taken as the main geometrical parameters.

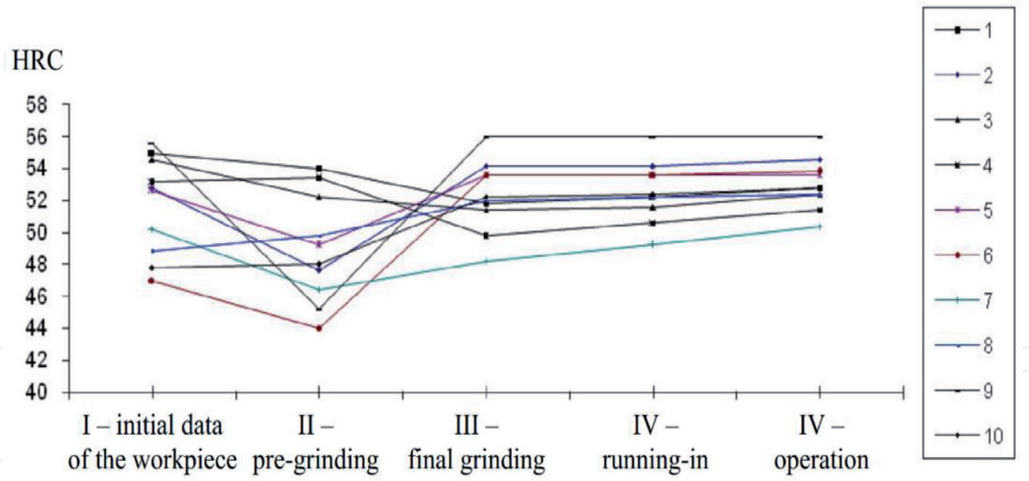


Figure 5.
The dependences of the changes in hardness of bearing journals by classes (no. 1–10) of camshafts in operations and stages (no. I–V).

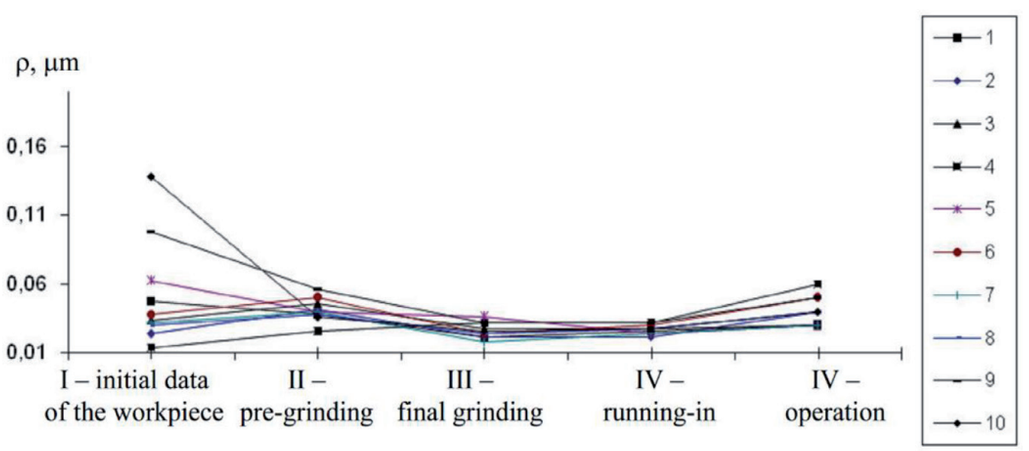


Figure 6.
The dependences of the changes in the radial runout of the bearing journals by classes (no. 1–10) of camshafts in operations and stages (no. I–V).

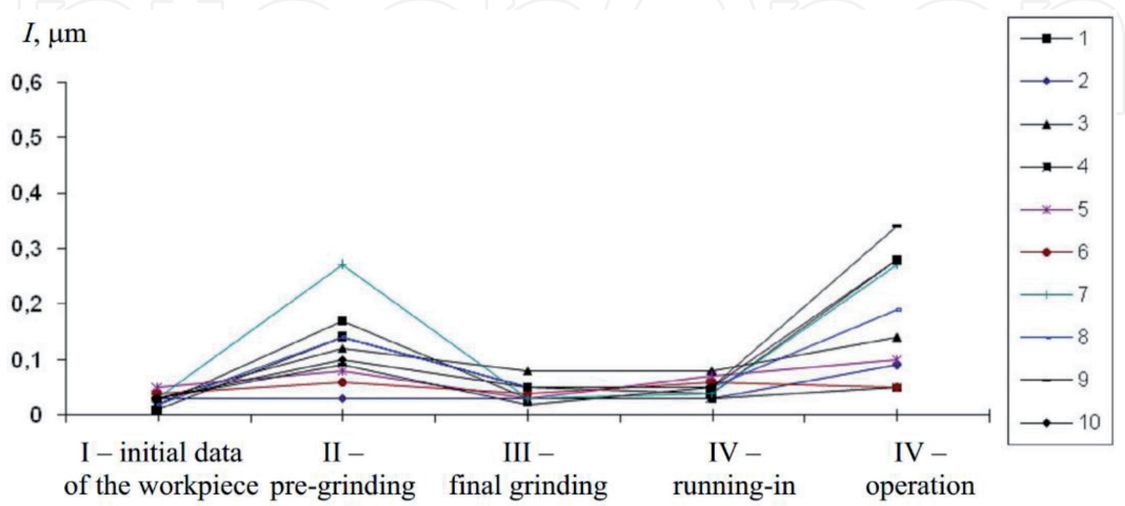


Figure 7.
The dependences of the changes in the dimensional accuracy of the bearing journals by classes (no. 1-10) of camshafts in operations and stages (no. I–V).

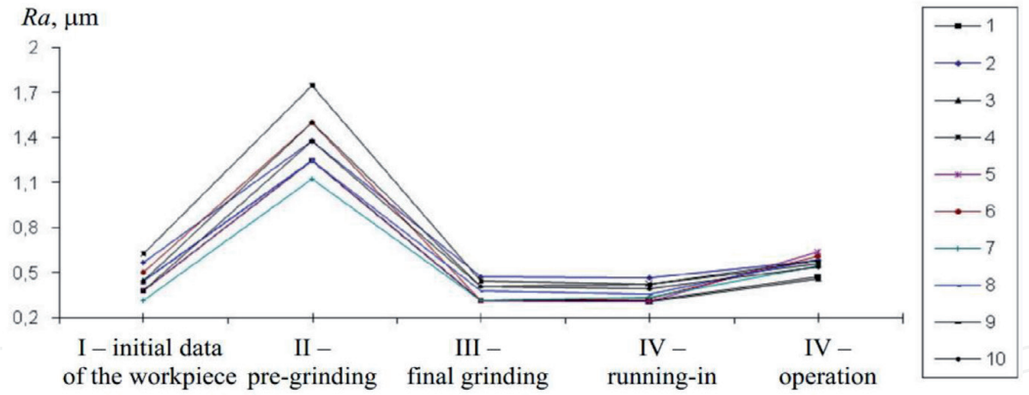


Figure 8.
The dependences of the changes in the surface roughness of the bearing journals by classes (no. 1–10) of camshafts in operations and stages (no. I–V).

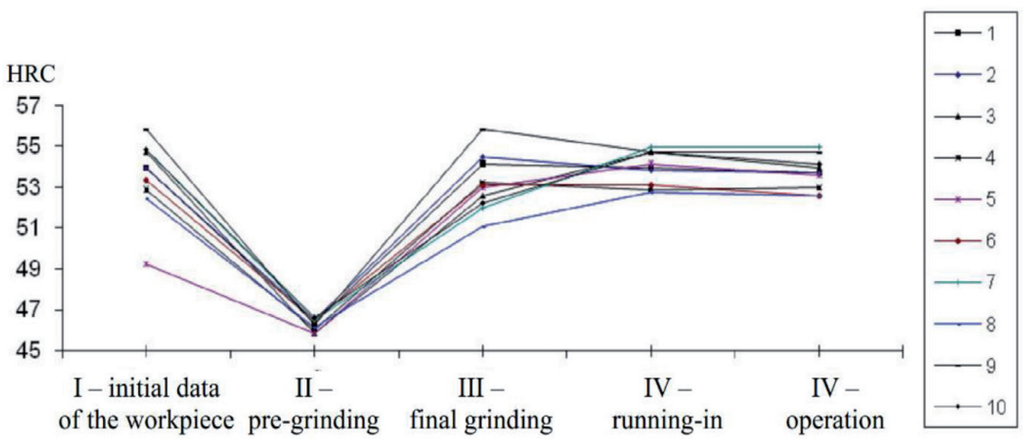


Figure 9.
The dependences of the cam hardness by classes (no. 1–10) of camshafts in operations and stages (no. I–V).

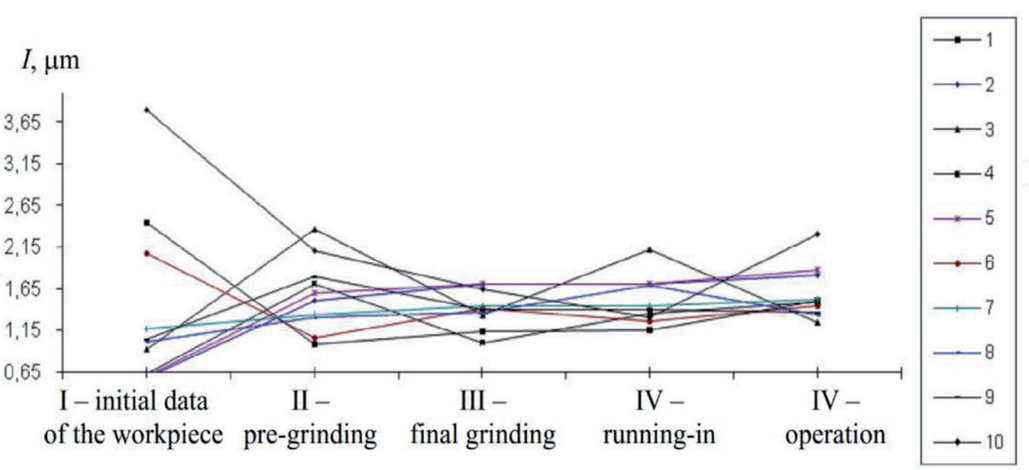


Figure 10.
The dependences of the changes in the dimensional accuracy of the cams by classes (no. 1–10) of camshafts in operations and stages (no. I–V).

The geometrical and physicomechanical parameters are interrelated; therefore, it is necessary to analyze the patterns of their changes in a complex in order to explain the mechanisms of the technological heredity associated with the interaction of properties. So, the radial runout of the surface during operation is greatly influenced by both the dimensional accuracy and its roughness, and with a

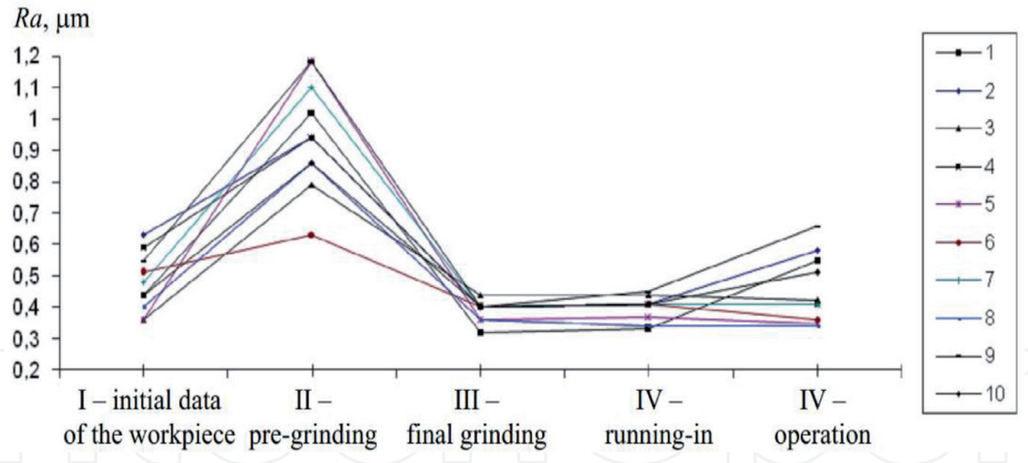


Figure 11.
The dependences of the changes in the surface roughness of the cams by classes (no. 1–10) of camshafts in operations and stages (no. I–V).

Recovery and operation	The quality parameters transfer coefficients			
	K^H	K^ρ	K^I	K^R
Workpiece—pre-grinding (K_1)	1.0568	1.2573	0.2500	0.3303
Pre-grinding—final grinding (K_2)	0.9369	1.5606	3.9024	3.6634
$K_{rg} = K_1K_2$	0.9901	1.9621	0.9756	1.2102
Final grinding—running-in (K_3)	0.9947	0.9635	0.9111	1.0092
Running-in—operation (K_4)	0.9913	0.6850	0.1800	0.6563
$K_{ro} = K_3K_4$	0.9860	0.6600	0.1640	0.6624
$K_r = K_{rg} \cdot K_{ro}$	0.9762	1.2950	0.1600	0.8016

Table 1.
The transfer coefficients K and the resulting heredity factors Kr for hardness H, shape deviations ρ, dimensional accuracy I, and surface roughness R of the camshaft bearing journals.

Recovery and operation	The coefficients of the mutual influence of quality parameters					
	$K^{H\rho}$	K^{HI}	K^{HR}	$K^{\rho I}$	$K^{\rho R}$	K^{IR}
Workpiece—pre-grinding (K_1)	1256.3107	323.5000	37.9806	0.3237	0.0380	0.0294
$K_{12} = K_1/K_2$	0.6771	0.2708	0.2885	0.3222	0.3432	0.0682
Pre-grinding—final grinding (K_2)	1855.3030	1194.6341	131.6667	1.0049	0.1108	0.4301
$K_{23} = K_2/K_3$	0.9724	1.0283	0.9283	1.7129	1.5463	3.8668
Final grinding—running-in (K_3)	1908.0292	1161.7778	141.8340	0.5867	0.0716	0.1112
$K_{34} = K_3/K_4$	1.4521	5.5260	1.5155	5.3528	1.4680	1.3882
Running-in—operation (K_4)	1314.0000	210.2400	93.5897	0.1096	0.0488	0.0801

Table 2.
The mutual influence coefficients K and the comparison coefficients Kc for hardness H, shape deviations ρ, dimensional accuracy I, and surface roughness R of the camshaft bearing journals.

Recovery and operation	The quality parameters transfer coefficients		
	K^H	K^I	K^R
Workpiece—pre-grinding (K_1)	1.1594	0.9061	0.5005
Pre-grinding—final grinding (K_2)	0.8698	1.1138	2.4593
$K_{rg} = K_1K_2$	1.0085	1.0092	1.2310
Final grinding—running-in (K_3)	0.9850	0.9365	0.9720
Running-in—operation (K_4)	1.0051	0.9503	0.8630
$K_{ro} = K_3K_4$	0.9900	0.8899	0.8389
$K_r = K_{rg} \cdot K_{ro}$	0.9984	0.8981	1.0326

Table 3.
The transfer coefficients K and the resulting heredity coefficients Kr for hardness H, dimensional accuracy I, and surface roughness R of the camshaft cams.

Recovery and operation	The coefficients of the mutual influence of quality parameters		
	K^{HI}	K^{HR}	K^{IR}
Workpiece—pre-grinding (K_1)	34.0339	56.5200	1.4453
$K_{12} = K_1/K_2$	1.0410	0.4714	0.3511
Pre-grinding—final grinding (K_2)	32.6943	119.8899	4.1169
$K_{23} = K_2/K_3$	0.9288	0.8949	1.1612
Final grinding—running-in (K_3)	35.2002	133.9736	3.5453
$K_{34} = K_3/K_4$	1.0365	1.1413	1.0976
Running-in—operation (K_4)	33.9623	117.3913	3.2299

Table 4.
The mutual influence coefficients K and the comparison coefficients Kc for hardness H, dimensional accuracy I, and surface roughness R of the cams.

relatively large surface runout, it is impossible to speak of high dimensional accuracy. The physicomechanical properties of the material have a significant impact on the geometrical parameters of the part.

According to the experimental data, the heredity mechanisms of operational quality parameters in the process of recovering the working surfaces of the UMZ-4173 engine camshafts were analyzed.

The hardness of the journal and cam surfaces at the stage of flaw detection gives a large scatter of data on the camshafts. This is due to the different condition of the shafts that came to overhaul. With an average hardness value of 55 HRC, the hardness of the shafts of no. 9 and 10 classes is significantly lower (44 HRC).

After restoration of a worn part by surfacing using a welding wire, the hardness drops sharply since the deposited layer without quenching does not have the hardness that the part had before the surfacing. But after heat treatment and subsequent finishing operations, the hardness is not only recovered, but in some cases reaches higher values than the initial workpiece had. This indicates that the hardening is carried out in full accordance with the technological process.

The classes of shafts, which at the initial stage had low hardness (no. 9 and 10), also have the lowest hardness values after the finishing treatment as compared to other classes. This obviously manifests the technological heredity.

Analyzing the geometric quality parameters, their dependence on the physicomechanical characteristics of the surface layer material should be taken into account. The initial radial runout of the camshaft bearing journals surfaces have a very large variation, which indicates a large wear of the bearing journals surfaces. After recovery operations, the runout values slightly stabilize (0.03–0.07 mm), but are still far from the required ones. After the final grinding, the values do not improve and more often remain at the same level. Moreover, in some classes, no. 10, the radial runout value deteriorates as compared to the initial one (from 0.01 mm on the initial workpiece to 0.03 mm on the recovered part).

These changes may be the result of editing operations that are carried out in the process of recovering parts. Editing a part, in addition to positive effects (elimination of residual bending, warping or twisting deformations), can also have negative effects on quality parameters.

The changes in the process of recovering the radial runout values in those classes of camshafts in which low surface hardness was noted (classes no. 9 and 10) is very ambiguous. This is a manifestation of the mutual influence of quality parameters in the technological heredity process.

When analyzing the dimensional accuracy of the camshafts surfaces, it should be noted that the changes in the accuracy of bearing journals and cams surfaces differ significantly. The bearing journals surfaces arrive for overhauls sufficiently rolled-in; therefore, a large deviation in the dimensional accuracy is not observed. The cams, on the contrary, have a large variation in the values of both the maximum cam size and the minimum one (i.e., the diameter of the cam base). This is due to varying degrees of wear on the cam surfaces.

After surfacing and turning operations, the scatter of the size values for bearing journals and cams is preserved and sometimes increases. But if, after finishing operations, the accuracy of the bearing journals is noticeably improved, although it does not reach the initial values, then the accuracy of the cams does not change, and sometimes (as in the case of class no. 10), it deteriorates compared to previous operations, which are also associated with the heredity phenomena.

The changes in the roughness of bearing journals and cams surfaces are unconventional for machining: after roughing operations, the roughness deteriorates in comparison with the initial condition, and in terms of finishing, it improves in comparison with the initial values. Moreover, the heredity processes are similar both on the bearing journals and cams, and the roughness parameters are less affected by other geometric or physicomechanical quality indicators.

5. Technological control of operational quality parameters

The study of experimental data allowed to determine the main dependences of the technological heredity of the physicomechanical and geometric quality parameters of the UMZ-4173 engine camshaft during the repair process. The transfer coefficients (**Tables 1** and **3**) show that the technological recovery and hardening processes are fundamentally different from the rational technological machining process. During machining in the manufacturing process, the harmful influence of the technological heredity is eliminated in the initial operations, while in the final operations, the heredity coefficients are stabilized.

When recovering during the repair process, both geometrical and physicomechanical parameters first deteriorate, and then they improve. However, in general, throughout the entire process, the physicomechanical characteristics are recovered, and the geometric, especially those associated with the surface microrelief, are even improved.

The mutual influence coefficients (**Tables 2** and **4**) allow to estimate the significance of both technological operations and technological factors in individual operations. Thus, the hardness of the material significantly affects the geometric parameters. For shape deviations, this effect is especially important in the initial operations. In other cases, it is stable in all technological transitions.

The geometrical parameters of the cylindrical surfaces of the bearing journals are weakly inherited; this is especially noticeable in the initial operations. Moreover, for the surface microrelief (its roughness), the recovery operations are technological "barriers" (since K^{pR} and $K^{IR} \to 0$). The further influence of the previous geometrical parameters on the subsequent ones is also not great and affects only the accuracy of processing.

The changes in the hardness of the bearing journals and cams of the UMP-4173 engine camshafts (**Figures 5** and **9**) show that the surfacing operations are technological barriers to the recovery of the working surfaces, and the final geometrical parameters of the surface quality are formed during finishing processing.

The high quality of repaired machines can be ensured by introducing new and traditional methods of recovery, hardening, and processing of machine parts [1, 2]. However, they have their own rational areas of application and do not always solve complex tasks of increasing the durability of products in specific operating conditions [6, 7].

Thus, the economical recovery of the extremely worn-out part surface to a given size is often not ensured with high quality parameters of hardening. Therefore, it seems rational to combine various methods of hardening and machining in the technological process of recovery, as well as various technological effects within the framework of the methods themselves [19–21].

In this regard, the technologies and equipment for combined hardening dimensional surface treatment of parts by applying ferromagnetic powders with electromagnetic welding in combination with surface plastic deformation (**Figure 12**) and welding of low-alloyed carbon wires in combination with rotary cutting have been proposed in order to recover the camshafts with varying wear degree of the working surfaces (**Figure 13**).

The combination of hardening, recovery, and surface treatment of parts in one technological process makes it possible not only to provide the necessary geometric characteristics of the surface during the recovery process but also to improve the physicomechanical properties of the surface layer material during hardening [19, 22, 23].

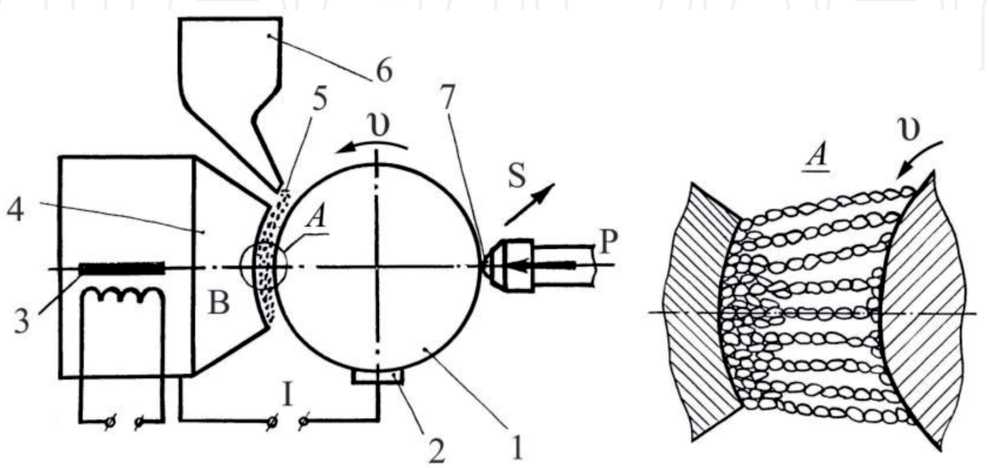


Figure 12.
Electromagnetic surfacing with surface plastic deformation: 1—workpiece; 2—sliding contact; 3—electromagnet; 4—pole piece; 5—ferromagnetic powder; 6—dosing device; 7–ball runner; υ—main speed; S—feed rate; P—deformation force; B—magnetic induction; I—electric arc current strength.

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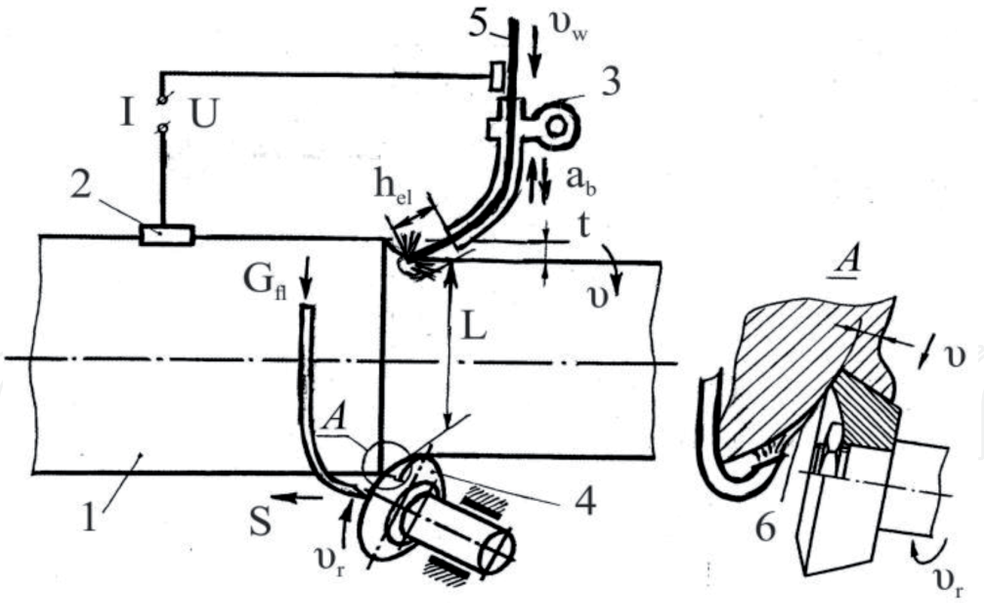


Figure 13.
Surfacing of wire with reinforcing rotational cutting: 1—workpiece; 2—sliding contact; 3—mouthpiece; 4—rotary cutter; 5—filler wire; 6—coolant; υ—main speed; υ_r—additional movement speed of the tool; S—feed rate; υ_w—wire feed speed; h_{el}—electrode overhang; a_b—vibration amplitude; G_{fl}—fluid flow; I—current strength; U—arc voltage; t—cutting depth; L—distance from electrode to cutter.

The study of the camshafts recovery showed that the surface hardness stabilizes (fluctuations within 3 ... 6 HRC) during electric arc surfacing of NP-30HGSA (the chemical composition of the wire %: C 0.25–0.35; Mn 0.8–1.2; Cr 0.8–1.2; Ni ≤ 0.40; Si 0.8–1.2; P ≤ 0.025; S ≤ 0.025) wire in a CO_2 environment, while the original parts had a significant variation (up to 30 HRC). After surfacing the wire, the hardness set in the technical documentation is ensured by subsequent heat treatment.

To eliminate the scatter of quality parameters of worn surfaces on the hardness of the surface layer and to ensure the physicomechanical properties of the layer located under the weld wire, it is recommended to use electromagnetic cladding (**Figure 14**).

When wear of the bearing journals surfaces exceeds the allowable limits, surfacing with wire is carried out on the insufficiently tempered surface. As a result, the hardened layer is formed on the surface basis not solid enough, which leads to the camshaft distortion. Preliminary hardening of the surface with ferromagnetic powder allows doping both the base and the surfaces formed during wire hardening (**Figure 15**) [18, 24, 25].

The surface geometrical parameters (radial runout ρ, dimensional accuracy IT, surface roughness Ra) after roughing are inherited in the finishing operations of grinding the bearing journals and cams of the camshaft. The geometrical deviations of surfaces after editing are saved on subsequent machining and assembly operations.

The analysis of the dependences of the influence of technological factors on the heredity of quality parameters made it possible to identify the determining processes of transferring properties when recovering, strengthening, and processing worn surfaces of the bearing journals and cams of the UMZ-4173 engine camshaft.

The analysis results showed that in the processes of electromagnetic surfacing of ferropowders and subsequent electric arc surfacing of NP-30HGSA wire on the bearing journals, as well as the arc current strength, magnetic induction, feed rates, and main processing movement affect the surface hardness in the process of plasma metallization of the cams using PG-10 N-01 (nickel-chrome base) powder. The determining parameter for quality control in the surfacing processes is the current strength.

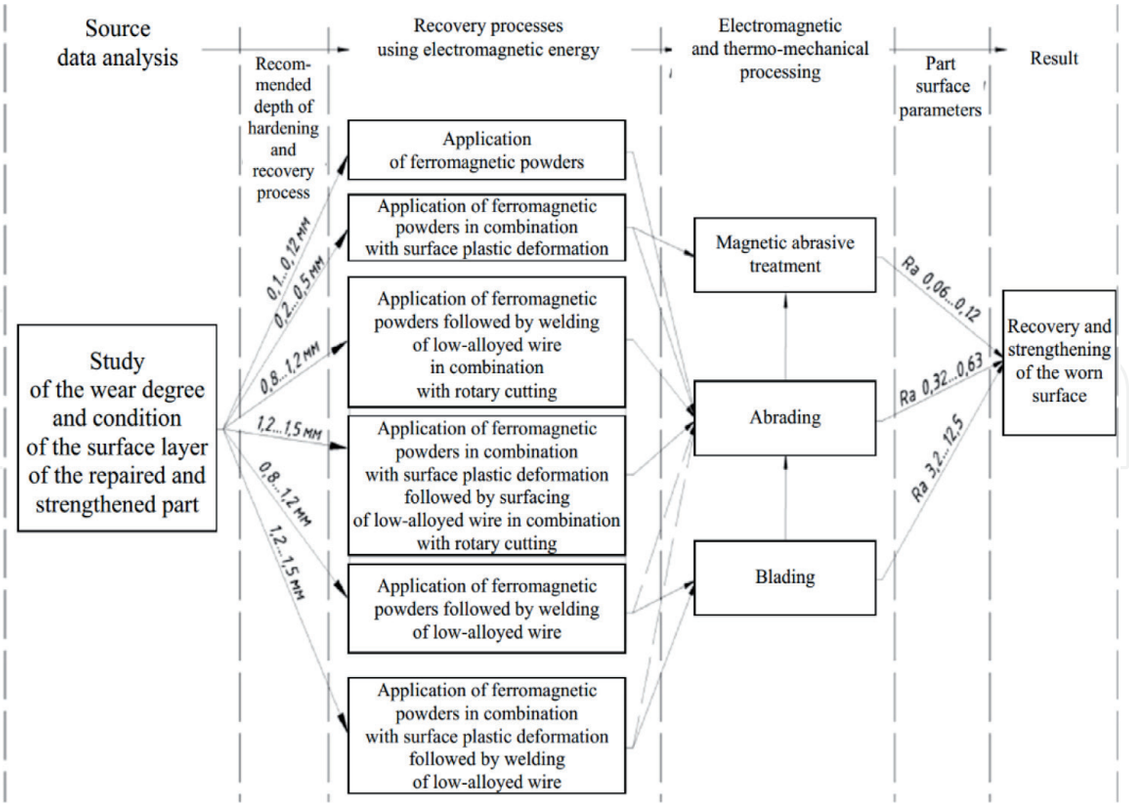


Figure 14.
The diagram of the recovery of the working surfaces of parts with varying wear degrees.

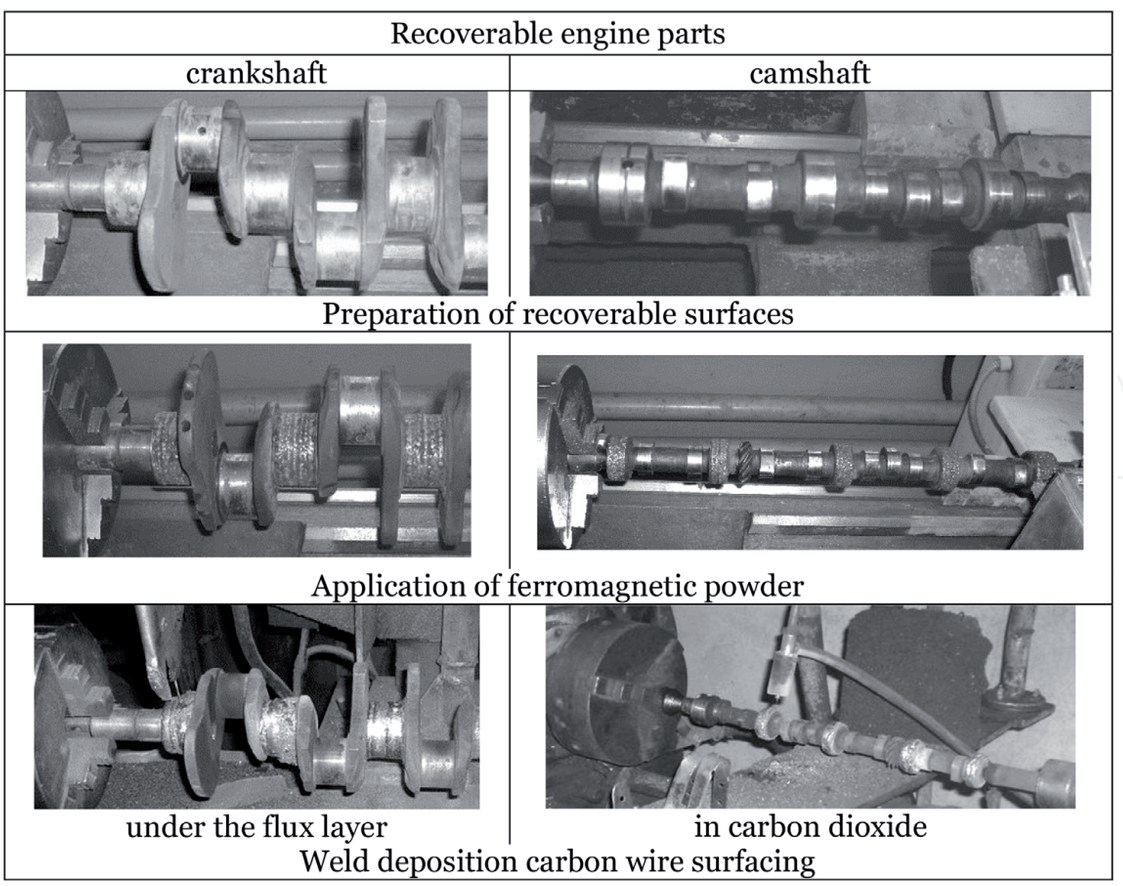


Figure 15.
Combined parts recovery technology.

In the final grinding, the hardness HRC and the roughness Ra of the surface are influenced by the radial and tangential components of the cutting force, which are determined by the depth of cut and feed during grinding, as well as the wheel and workpiece rotation rates.

Therefore, in controlling the machining quality, the focus should be on the depth of cut and the feed of the grinding wheel. The use of magnetic abrasive machining of polished profile surfaces can significantly reduce the duration of rolling operations.

According to the studies on the route of recovery operations, it was recommended: to provide stable hardness and uniformity of the coating material in the process of surfacing, and high surface hardness (54 ... 56 HRC) in the process of tempering; to eliminate straightening operations when recovering the camshaft to reduce the mutual radial runout of the surfaces to 0.02 mm; and to ensure the required accuracy of working surfaces.

The conducted research allowed to identify the processes of transferring the properties during recovery, hardening, and surface treatment with varying wear degrees of the bearing journals and cams of the UMZ-4173 engine camshaft, and to develop regulations for the technological process operations in accordance with them [26, 27].

6. Conclusions

The technological heredity of operational properties in the processes of manufacturing machine parts is advisable to describe by the graph reflecting the coefficients of transmission and mutual influence of physicomechanical and geometric parameters. To calculate the heredity coefficients according to the degree of the influence significance, a sequence of parameters is recommended: hardness, shape deviation, dimensional accuracy, and surface relief roughness of the part surface.

Methods of technological management and control of the heredity of operational properties of parts include: measurements of physical, mechanical, and geometric parameters of the most critical parts; determination of technological heredity mechanisms on the basis of transfer coefficient and coefficient of mutual influence of operational properties; analysis of technological barriers during intensive effects of energy flows; and development of measures for technological management of technological processes.

The technological heredity in the process of recovering the bearing journals and cams of the camshaft is non-monotonous and is fundamentally different from rational heredity with monotonous transfer of properties during machining, while 10–20% of indicators related to the shafts, the working surfaces of which are worn out with more than acceptable values, are out of the general dependence of the quality parameters transfer.

When recovering the surfaces, the geometrical and physicomechanical quality parameters of the camshafts first deteriorate and then improve; so the heredity is described by transfer and is determined by a uniform change in the hardness of the bearing journals and cams, and upon completion of the technological process, the geometrical characteristics are better than the original ones on worn surfaces, and the physicomechanical properties are recovered completely.

According to the study of the properties transfer processes when recovering the worn surfaces, it was recommended: to control the deformation of the part after machining operations; to eliminate the editing operation after heat treatment; to use a combination of methods and a combination of technological effects in recovering the parts surfaces with wear exceeding the limit values; to ensure stable

physicomechanical properties of coating materials in the processes of surfacing and subsequent tempering; and to regulate the depth of cut and the supply of an abrasive wheel when grinding the recovered surfaces.

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