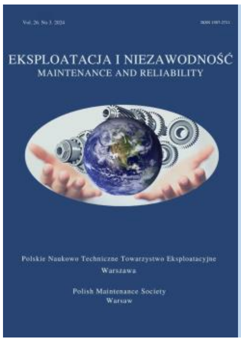

Eksploatacja i Niezawodnosc – Maintenance and Reliability
Volume 26 (2024), Issue 3
journal homepage: http://www.ein.org.pl

Article citation info:
Kusyi Y, Stupnytskyy V, Kostiuk O, Onysko O, Dragašius E, Baskutis S, Chatys R, Control of the parameters of the surface layer of steel parts during their processing applying the material homogeneity criterion, Eksploatacja i Niezawodnosc – Maintenance and Reliability 2024: 26(3) http://doi.org/10.17531/ein/187794.

Control of the parameters of the surface layer of steel parts during their processing applying the material homogeneity criterion

Indexed by:

Yaroslav Kusyi[a], Vadym Stupnytskyy[a], Olha Kostiuk[b], Oleh Onysko[c], Egidijus Dragašius[d], Saulius Baskutis[d], Rafał Chatys[e,*]

[a] Lviv Polytechnic National University, Department of Robotics and Integrated Mechanical Engineering Technologies, Bandera st. 12, 79013 Lviv, Ukraine
[b] Lviv Polytechnic National University, Department of Marketing and Logistics, Bandera st. 12, 79013 Lviv, Ukraine
[c] Ivano-Frankivsk National Technical University of Oil and Gas, Department of Computerized Mechanical Engineering, Karpatska st. 15, 76000 Ivano-Frankivsk, Ukraine
[d] Kaunas University of Technology, Faculty of Mechanical Engineering and Design, Department of Production Engineering, Studentu st. 56, 51424 Kaunas, Lithuania
[e] Kielce University of Technology, Faculty of Mechatronics and Mechanical Engineering, Department of Mechatronics and Weapon Engineering, al. Tysiąclecia Panstwa Polskiego 7, 25-314 Kielce, Poland

Highlights

- Assessment of the material's physical structure hemogeneity during processing in the technological chain "blank - workpiece - final part" is presented.
- LM-hardness method was used to evaluate the quality of the material structure and damageability.
- The concept of technological damageability is used as a criterion evaluating the technological process of the being manufactured parts
- The method for assessing and analysing the dynamic alterations in material homogeneity of machine components at machining has been developed, successfully tested and implemented.

Abstract

The main goal of the presented research is to assess the technological damageability of the material and use this as a criterion for analyzing the technological route of product machining in the "blank-workpiece-final part" technological chain. This technological chain is examined in detail in the most important stages of the life cycles of mechanical engineering products aiming to take into account the principles of technological inheritability of their characteristics and quality parameters. The technological inheritability of the properties of the surface layers of the made of steel parts of machines and mechanisms during their machining evaluates and predicts the transformation of the structurally heterogeneous material obtained after the production of blanks into the structurally homogeneous material of the final parts. The procedure for evaluating the homogeneity of the processed material for each technological step by the LM hardness method is presented according to the calculated values of the Weibull homogeneity coefficient, material constant, variation coefficient, technological damageability along with corresponding intensity of the expansion. The developed methodology was implemented and proven at the manufacturing process of the conveyor belt drive drum shaft.

Keywords

life cycle of a part, reliability, surface layer, technological inheritability.

1. Introduction

Priority directions of the research of the reliability theory of technical systems [4, 9, 17, 24] have changed very dynamically in the last decades, which is relatedto the increasing requirements for mechanical engineering parts and products [2, 8]. New approach [18, 19] to the technological processes of the parts and assemblies manufacturing aiming to

---

(*) Corresponding author.
E-mail addresses: Y. Kusyi (ORCID: 0000-0001-5741-486X) jarkym@ukr.net, V. Stupnytskyy (ORCID: 0000-0003-0006-9932) vadym.v.stupnytskyi@lpnu.ua, O. Kostiuk (ORCID: 0000-0002-3499-2787) olha.s.kostiuk@lpnu.ua, O. Onysko (ORCID: 0000-0002-6543-9554) onysko.oleg@gmail.com, E. Dragašius (ORCID: 0000-0001-6610-6797) egidijus.dragasius@ktu.lt, S. Baskutis (ORCID: 0000-0003-3160-888X) saulius.baskutis@ktu.lt, R. Chatys (ORCID: 0000-0002-2168-286X) chatys@tu.kielce.pl

achieve the most efficient operational parameters and reliability criteria is related to the implementation of the principle of functionally-oriented design [13, 53], increase the role of technological inheritability at all phases and stages of their life cycles [10, 11, 39] (Fig. 1). This should be considered in further mechanical engineering research. The most important tasks of designers, engineers, technologists, and scientists are determined by certain requirements for strength, rigidity, stability, fatigue, system reliability, safety, risk, security of mechanical engineering parts, structures and machines [30].

In the machinery and equipment manufacturing industry, one of the key aspects of technical systems is the operational safety and reliability of equipment, which includes careful investigations of failures and their consequences. It depends not only on ensuring the detailed accuracy characteristics and parameters of the surface layer, but also on the operational characteristics and reliability indicators of the technological system. Along with other indicators, all quality parameters of mechanical engineering parts and mechanisms are closely correlated with the main phases and stages of their life cycles identified in the most important directions of Industry4.0 [34, 35].

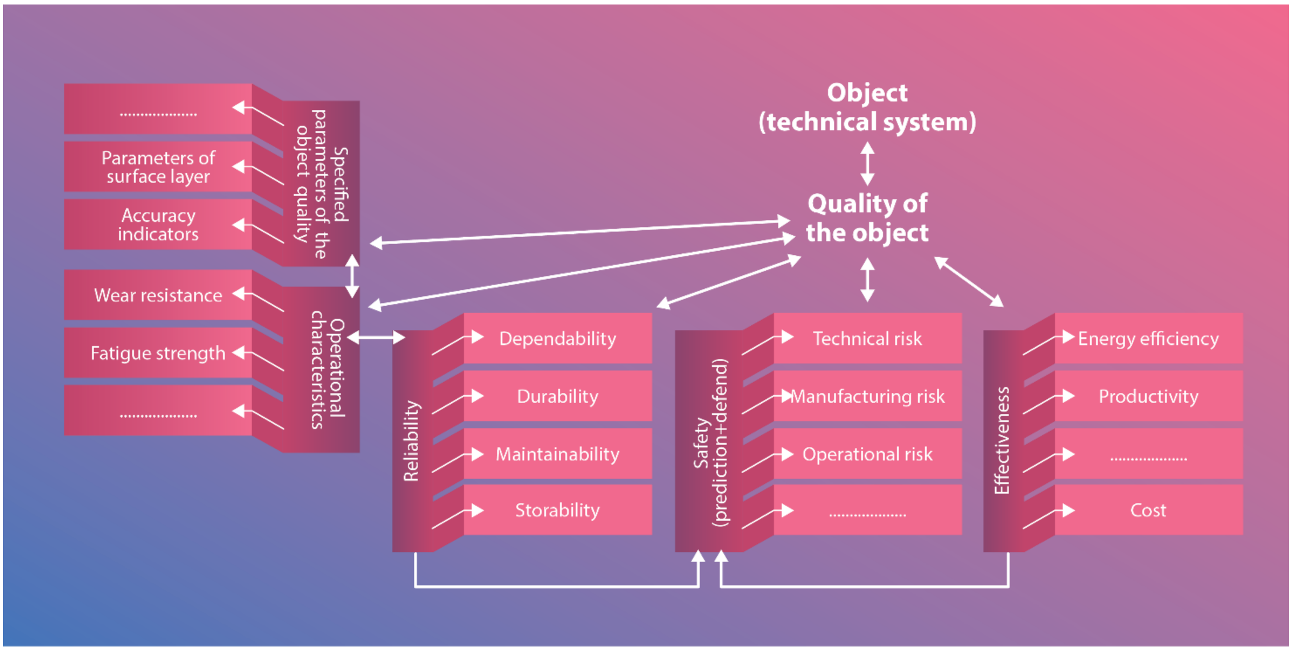

Fig. 1. The main characteristics of the modern technical system.

Sustainability in general and sustainable manufacturing and machining in particular are closely related to the main requirements of Industry4.0/5.0. Nowadays, sustainable machining is created within the framework of environmental protection. Environmentally friendly machining allows you to reduce the consumption of cutting fluids and the required production power at machining. On the other hand, the restriction or refusal touse the cutting fluids leads to a decrease in cutting modes and increasing of piece–calculation time and its elements at parts machining, which requires more attention to the conditions of the formation of the surface layer of the parts. Thus, technological inheriatability of material properties has gained increasing importance at parts machining to analyse the relathionships in technological chains "blank - workpiece - final part". Carriers of heritage information in product manufacturing are surface engineering and materials. The development of methods for estimating the material behaviour of the parts surface layer, forecasting degradation processes at machining of machine parts, and mathematical description of physical phenomena in the surface layers of machine parts is an urgent task in mechanical engineering.

Research of finishing and finishing-strengthening technological operations at planning of technological processes of detail production [3] is carried out more intensively than the systematic analysis of the hereditary properties of parts materials at their manufacturing and operation. At the substage of production design and technological preparation, it is difficult to determine the value of all technological indicators at the production of parts and assembly of machines and to predict their importance at certain time intervals during the life cycle of the part or mechanism [12]. Consequently, technological defects are formeddue to structural stress concentrators at parts manufacturing. Under conditions of intensive operation, due to wear, corrosion, fatigue, etc., significant contact stresses are formed in the surface layers of the mating surfaces of machine parts. As a result, the prerequisities are created for technological defects to develop into damage to the surface layers of the part, as well as their subsequent destruction and failure of parts and machines with catastrophic consequences for the environment (Fig. 2).

The useful life of machines and mechanisms depends on the physical and mechanical properties of materials from which the parts are made and the coatings [7, 42, 43, 49, 51] used to cover the surfaces of the parts, the parameters of manufacturing accuracy [6, 46] and the functional surfaces of machine parts quality indicators of the surface layers [5, 48], including the technological characteristics of products geability at manufacturing and wear at operation [50] throughout the life cycle of engineering products [31].

However, at present, there is a lack of comprehensive theoretical as well as experimental research considering the assessment of the potential technology damageability of the material during the development and creation steps of the machine parts life cycle, and pursuing aim to designa rational route of surface processing and analyse the degradation processes of the material surfaces. At machining of parts, there is a lack of an effective criterion for evaluating the degree of material degradation, which would fully take into account the changes in the properties of the surface layer and surface quality parameters. In addition, indicators correlating with the structural state of the processed material of the machine-made product and determining the homogeneity parameter of its structure according to the degree of dispersion of the hardness characteristics after mechanical processing are insufficiently developed.

Most research on technological inheritability has focused on the relationship between the surface layer parameters of parts and their operational characteristics (abrasive wear as well asresistance to corrosion, fatigue strength and etc.). In addition, the destruction criteria developed to assess the level of material degradation of parts are usually narrowly specialized for specific operating conditions and specified parts. Further research in this area should consider a generalized criterion, according to which it would be possible to assess the level of degradation of material quality of parts at their manufacturing in the technological chain "blank-workpiece-final part", using the technological inheritability of material properties.

The aim of the work is to develop a technique for controlling the parameters of the surface layer of the material, applying the indicators of the homogeneity criteria of the material, which would be used for the mechanical processing of parts in order to obtain the best surface properties of the material.

2. Teoretical insights

The quality parameters of parts and machines, the cost and productivity of technological processes at products machining are provided by the structure of relationships and properties of the technological system: metal-cutting machine - clamping device - metal-cutting tool - workpiece, which describe the physical content of physical and chemical processes in the machine:

$$y = f(x_1, x_2, \dots., x_n), \tag{1}$$

where: y is a parameter of the service purpose of the machine; x_1, x_2, ..., x_n are parameters of connections between executive (functional) surfaces of parts in the machine.

The original method of investigations the behavior of elements of the technological media: metal-cutting machine - clamping device - metal-cutting tool at products machining is proposed in [30].

Equations (1) are transformed at the stage of design and technological preparation of production [31]:

$$y = f\big(\varphi_1(V_1, V_2, \dots, V_n), \varphi_2(t_1, t_2, \dots, t_m), \dots, \varphi_k(r_1, r_2, \dots, r_l)\big) \tag{2}$$

where: $\varphi_1(V_1, V_2, \dots., V_n)$, $\varphi_2(t_1, t_2, \dots., t_m)$, ..., $\varphi_k(r_1, r_2, \dots., r_l)$ – parameters of dimensional relations between the executive surfaces of the machine.

Complexities of taking into account all relationships and interactions (1), (2) at parts machining leads to the emergence of structural and technological stress concentrators and the formation of technological defects. Technological defects can evolute into damages at the stage of operation of parts and machines due to the difficult working conditions of mechanical engineering products.

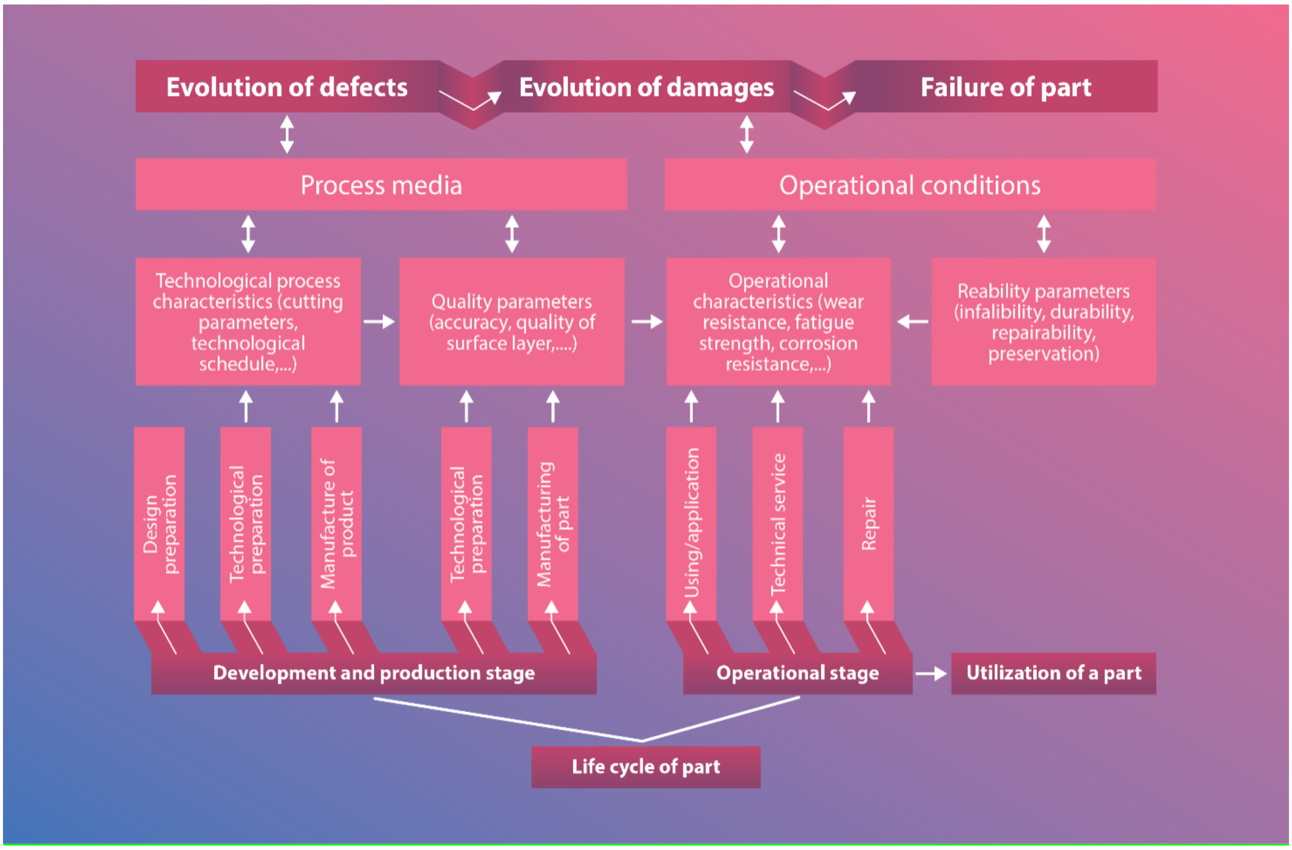

Fig. 2. Analysis of life cycle of a part.

2.1. Methods of material homogeneity damage analysis in assessing the degree of damage

Wear of most mechanical joints, as a characteristic type of damage to machine parts, is determined by fatigue processes resulting from fatigue microcracks and detachment of material particles or its oxide films in the process of repeated loading of individual friction surface irregularities [21].

In the mechanics of materials, the use of the terms "damaging (damage)" and "damageability" is determined by the duration of the physical and chemical processes that accompany both the manufacturing of parts and their operation. Fleeting and medium-speed processes are referred to development and creation stage of machine parts and are characterized by the damageability of the material of blanks and workpieces in their life cycles due to the formation of technological defects. On the contrary, medium-speed processes and slow processes are determined by the damage the material of blanks and workpieces when technological defects transform into damage at the operational stage of machine parts in their life cycles. This approach makes it possible to distinguish the processes that lead to the formation of failures and loss of machine performance, and to predict their evolution at various substages and stages of the life cycles of parts or machines [14, 47].

Conversely, the term “damaging“ is rather difficult to characterize. Density of volumetric or surface defects, the average distance between them, etc. are often used as the simplest damaging indicators in the analysis of the damage of materials of machine parts. Internal friction, sound velocity, electrical resistivity, etc. are physical parameters that correlate with damaging [28].

Typically, the consequence of damageability is the result of technological defects due to structural stress concentrators and technological process imperfections at various substages of their design and manufacturing. The damaging results the damage characterized by a change in the structure, geometric and physical-mechanical properties of the surface layers in the processes of machining of mechanical parts [15, 20, 54].

Damageability in the general case characterizes the homogeneity level of a material at parts manufacturing or their operation due to the different degradation processes at important phases and stages in their life cycles [30].

2.2. The use of macrohardness for the analysis of wear processes in friction joints

The operating conditions of mechanisms and their parts have a priority effect on the assessment of hereditary characteristics when planning technological processes in the stages of the design and technological evaluation of parts manufacturing and assembly of mechanisms in their life cycles (Fig. 2). It was established [8, 19, 30] that wear is the dominant type of different surface damages in the most mating surfaces ofmechanical engineering parts at their operation. It is obvious, the functional surfaces of axles, shafts, crankshafts, housing holes, gears, guide sleeves, hubs, etc. work in operational conditions of friction, intensive wear, fatigue and etc. Under such operating conditions, a high-quality surface layer of the parts’ functional surfaces, which ensures technological structural homogeneity, is a desirable condition for the reliable functioning of the parts and machine [25, 30].

The processes leading to damage and failure of machine parts [28]: plastic deformation, which changes the stress-strain state of the parts and machines; fatigue under static and cyclic loads; thermal destruction due to a change in the structure of the material when heated to a critical temperature; destruction under the influence of an aggressive environment; wear of parts and products due to friction.

Technological defects, appeared at development and manufacturing stages of mechanical engineering parts' life cycle, during operation are influenced by various factors, such as temperature, shocks, magnetic and electric fields, vibrations, aggressive media, friction, torques, loads, etc., and transform into damages.

A considerable number of scientists have dedicated their work to detailed studies of the mechanisms of transformation of technological defects in the surface layers of parts, to forecasting their evolution at various substages and stages of the parts' life cycles [26, 27, 29, 33, 38, 45, 55, 56].

Wear is characterized by the process of separating the material from the friction surface of a solid body and/or increasing its residual deformation under friction conditions, which is accompanied by a gradual change in the size, shape and/or mass of the body [21, 37, 44].

Defects in the materials of machine parts, as stress concentrators, are associated both with the imperfection of the structure of solid bodies and with the consequences of various influences (a mechanical, thermal, blade, abrasive machining, etc.). The main influence on the wear process is determined by the constant occurrence and violation of frictional bonds, which have a dual molecular-mechanical nature. Wear is associated with repeated disruption of frictional joints. Repeated plastic deformations due to the formation or disruption of friction bonds sharply increases the number of defects and changes the mechanical properties of the crystals [30].

Clusters of dislocations are stress concentrators in the presence of obstacles in the sliding plane that lead to the formation of microcracks according to Mott's theory of dislocation defects. It is known that the destruction of a solid body occurs when the tensile stress applied to it reaches a value equal to the theoretical strength [28].

From a tribological point of view, failures of the tribological mating surfaces of parts and machines are a common cause of their damage and failure. Failures are caused by an incorrect approach to design and technological pre-production and manufacturing of parts, when previous production experience is taken too much into account and quality control of designed tribological couplings is not organized according to the rational test cycle (RTC). RTC is a set of successive stages of tribotechnical tests, which gradually become more complicated (mainly on small-sized samples) according to a previously developed plan of technological experiments. Taking into account the available results of the RTC, material combinations that do not have significant advantages over serial ones are gradually screened out. At the same time, the durability of tribological couplings and frictional losses are estimated with a sufficiently high accuracy at the relevantRTC stages, taking into account the fact that friction and wear are caused by a large number of phenomena and are characterized by various mechanisms of destruction of parts' contact surfaces [1, 23].

Five generalized parameters (surface hardness *HB*, specific load p_a, wear intensity j and two friction joint characteristics related to shear resistance gradient) are used to describe friction and wearprocesses [28].

It was established that the wear characteristics are related to the macrohardness *HB* (*H*) of the surface layer of parts:

- specific frictional wear i_h:

$$\boldsymbol{i_h} = \frac{\boldsymbol{j \cdot HB}}{\boldsymbol{p_a}} \tag{3}$$

- wear *U* (for specified operating conditions)

$$\boldsymbol{U} \approx \frac{\boldsymbol{q}}{\boldsymbol{HV}}, \tag{4}$$

$$U = K_S \cdot K_W \cdot \left[\frac{P_i}{f(HV)}\right]^{\beta}, \tag{5}$$

- relative wear resistance ε

$$\varepsilon = b \cdot HV, \tag{6}$$

where: q is the load; K_S is a constant depended on the grain shape; K_W is a constant depended on the material of the abrasive grain; P_i is the specific load per one grain; $f\,(HV)$ is the hardness function; β is the exponent; *HV*– hardness according to Vickers; *b* is the parameter of the proportionality (*b*=7.3).

Seven criteria for the characteristics of the material properties of friction joints are proposed for evaluating the performance of friction pairs, in particular, macro-hardness, compatibility, microhardness, structure change, stress state of the friction element, workability, friction-wear characteristics [28].

The review of the literature shows that the hardness of the material from which the parts are made has a considerable influence on wear of the surfaces of the parts working under conditions of intense friction. In this way, the hardness of parts' surfaces in studies of technological inheritability of qualitative parameters in the machining of parts that are exposed to intense wear and loads during operation, is singled out as an indicator in assessing the material degradation processes as well as their influence in the planning of technological processes for the manufacturing of machine parts.

2.3. Analysis of damaging and damageability of parts material using LM-hardness method

The development of the theory of Continuum Damage Mechanics [15, 20, 40] allows to analyze the causesof the deterioration of the physical and mechanical properties of parts materials. However, the lack of a physically and experimentally based criterion to properly assess the level of current damageability in the existing material restrains the effective implementation of this approach. This problem is especially relevant when monitoring the residual resource of structural elements (for example, before the initiation of microcracks in the material) during long-term operation.

In order to evaluate changes in material properties and the development of these changes in mechanism parts during operation, it is important to evaluate defined physical and mechanical characteristics. One of these characteristics is the hardness of the material, based on the measured values of which the analyses of strength and plasticity of the material of mechanical parts isconducted. Hardness, on the other hand, is a measure of a material's resistance to deformation, which allows us to assess the material's brittleness and plastic deformations.

However, it should also be appreciated that the hardness test primarily measures the material's resistance to deformation on or near the surface of the part. Therefore, hardness values may not be very informative for certain types of structural changes or changes occurring in deeper layers of the material. Thus, the relationship between hardness and other mechanical properties such as tensile strength or yield strength is not always adequate [16, 32]. This correlation may vary depending on the chemical composition, heat treatment or microstructure of the material. In addition, the results of hardness measurements depend on many factors, such as the chosen measurement method, sample size and shape, material anisotropy, indenter effects, surface preparation and conditions, variations in temperature, so it is necessary to emphasize the fact that the results of absolute hardness measurements of materials are interpreted ambiguously. Therefore, hardness is accepted as a generalized characteristic that helps to evaluate the elastic-plastic properties of materials, especially as it relates to machine parts and engineering applications [22].

Most often, the average hardness value obtained by conventional hardness measurement methods is used to evaluate the surface layer of machine and mechanism parts. Meanwhile, the LM hardness method proposed under the guidance of Academician A.A. Lebedev at the G.S. Pisarenko IPS NAS of Ukraine, provides a radically different approach for evaluating transformations in material surface layers of machines' parts [36, 41]. Lebedev in his works made a theoretical justification, which was later confirmed during experiments, stating that when assessing the structural state of a material, it is appropriate to rely on the absolute values of the material properties, paying attention to the dispersion of the results obtained for the same specimens under the identical conditions. This method has rather easy implementation in engineering practice where value of hardness, as a mechanical parameter, is applied to indirect property evaluation. The LM-hardness methodology includes evaluation of the hardness dispersion as a crucial mechanical parameter of the material of machine and mecganism parts [30, 41].

The Weibull distribution is applied for solving the physics of metals tasks, in particular in the development of statistical theories of strength [26]. Meanwhile, homogeneity is an indicator that describes the material condition of machine parts and is used to evaluatethe hardness measurements' results. Homogeneity is determined using the Weibull distribution [36, 41]:

$$P(\sigma) = 1 - e^{-\left(\frac{\sigma}{k}\right)^{m}}, \qquad (7)$$

where: σ – tension; *k*, *m*– parameters of the Weibull distribution.

A structurally sensitive parameter namely: Weibull homogeneity coefficient *m* determines a level of structure degradation. It is calculated by [31, 32]:

$$m = d(n) / \Big(2{,}30259 \cdot S\big(\ell g(H)\big)\Big), \qquad (8)$$

$$S\big(\ell g(H)\big) = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} \left(\ell g(H_i) - \overline{\ell g(H)}\right)^2}, \qquad (9)$$

$$\overline{\ell g(H)} = \frac{1}{n} \cdot \sum_{i=1}^{n} \ell g(H_i). \qquad (10)$$

where: *S* is the area of the boundary of the structural element; *d*(*n*) denotes a parameter that estimatesa number of measurements *n*.

In practical applications related to mechanical engineering other static parameters are used to estimate the degree of degradation of the parts material. The coefficient of variation, which evaluates the degree of dispersion of hardness measurement results compared to its average value [25]:

$$\nu = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} \left(H_i - \overline{H}\right)^2} / \bar{H}, \qquad (11)$$

where: $\overline{H}$ is the average hardness value of the material of the parts.

The relationship between the sizes of present defects in the being tested specimen determines the structural heterogeneity of a research element. The substantial influence, which the statistical factors have on the strength of structurally heterogeneous element takes place through out the progression of cracks, which is resulted by the acting normal stresses. The structural inhomogeneity of the parts'material is defined by the Weibull homogeneity coefficient (*m*), in particular: $m < 10$ – for structurally heterogeneous materials; $m \geq 10$ – for structurally homogeneous materials [30].

The heterogeneous structure of the parts'materialis evaluated at the macro-, micro- and sub-micro levels in accordance with both the physical as well as mechanical characteristics. The structural heterogeneity of the material during the manufacturing of machine parts is determined by the chemical composition of the material, the technology of obtaining and molding of workpieces, the appearance of macrodefects (inclusions, pores, etc.) after the workpieces are formed and processed technologically [25, 30].

The *P* function of the influence of statistical factors on crack development is determined by formula:

$$P = A_m^{1-I(\sigma)}, \qquad (12)$$

where: A_m is a material constant that depends on the provenance of existing defects; $I(\sigma)$ is the stress function that determines "stiffness" of the load.

The constant A_m reflects the statistical essence of the process of material damage and destruction:

$$A_m = \left(\frac{1-q}{q}\right)^{\beta}, \qquad (13)$$

where: *q* is the probability of distress for continuousness in any of the *n* problematic cross-section of the material

$$q = \sum_{i=1}^{n} \frac{n_i}{n} q_i. \qquad (14)$$

The constant Am is determined on the basis of the obtained results of tensile, compressive and torsional strength tests of the material [30]:

$$A_m = \frac{\sigma_{eq.} - \sqrt{3}\cdot\chi\cdot\tau_{\kappa}}{(1-\chi)\cdot\tau_{\kappa}}, \qquad (15)$$

where: $\sigma_{eq.}$is the equivalent tension; χ is the material constant, which characterizes the degree of influence of shear deformation in the macrodestruction, which affects the weakening of the material and the formation of cracks; τ_{κ} is the limit of the material's torsional strength.

The mathematical relationship related to the non-destructive monitoring methods of material state is determined using the condition of equivalence of brittle fracture probabilities according to the Weibull theory [39] regarding bending and torsion:

$$A_m = \left(\frac{m+2}{4m+4}\right)^{\frac{1}{m}}, \qquad (16)$$

where: m denotesthe homogeneity coefficient of Weibull distribution.

A characteristic feature δ was proposed to estimate the intensity of damage growth [41]:

$$\Delta m = (m_{in.} - m_{cur.})/m_{in.}, \qquad (17)$$

$$\delta = (m_{in.} - m_{cur.})/m_{cur.}. \qquad (18)$$

where: $m_{in.}$, $m_{cur.}$ are the values of the Weibull homogeneity coefficients (m), measured for the initial and current state of the parts material, respectively.

3. Research methodology

3.1. General provisions

The planning of technological processes for the manufacturing of parts is considered, consisting of n operations, from the obtaining of the workpiece to the production of the final part (see Fig. 3). The technological inheritability of the parameters of the part quality and material properties settlea set of restrictions for the being executed *i-th* technological operation ($i \in [1;\ n]$), which predefine the machining accuracy, surface layer quality, shape deviation, mutual position between surfaces and material characteristics following the requirements as indicated in design specification and in technology related documents (Fig. 3).

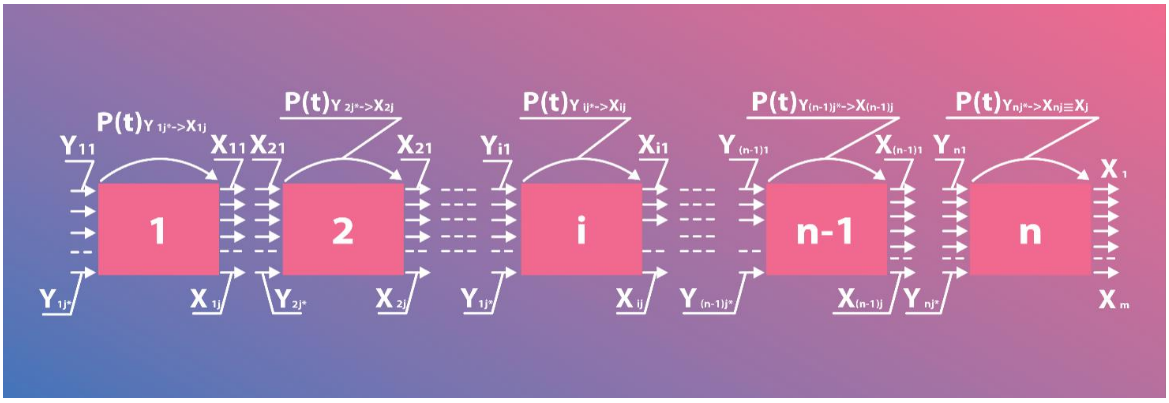

Fig. 3. Schematic diagram of the part manufacturing process.

Input parameters Y_{11}.... Y_{1j*} of a certain technological process of part manufacturing are formed from the initial parameters of the technological process of blank manufacturing. The input parameters of the blank Y_{ij*} are transformed into the output parameters of the workpiece X_{ij} after performing a certain technological operation due to the influence of the technological system: machine tool –clamping device – cutting tool - workpiece and the technological inheritability of the properties and characteristics of thepart (Fig. 3). The probability of not rejecting the workpiece during the *i-th* technological operation according to the *j-th* technological parameter predicts that the specified parameter of the part will be obtained within the limits of the tolerance regulated by the technical requirements. Fulfillment of the condition $j^*=j$ or $j^*\neq j$ is ensured by regulated technological tasks for the specified technological operation. When solving this technological task, the condition is accepted that the initial parameters of the previous technological operation $X_{(i-1)j}$ do not undergo changesbefore the execution of the current one. Therefore, the assumption about the identity of the output parameters of the previous technological operation and the input parameters of the next (current) technological operation is valid: $X_{(i-1)j} \equiv Y_{ij^*}$.

The determined *x-th* functional surface of the FS_x part (FS_x – *x-th* functional surface) is characterized by the technological inheritability of a quality parameters'set: machining accuracy, geometric (form deviations and mutual arrangement of surfaces, waviness, indicators of roughness and submicro-roughness) along with the physical and mechanical quality parameters of the surface layer by applied principle related to the object-oriented design: $FS_x =$

$$\left| \begin{array}{l} \{TOp_{x1\_as} \cdots\cdots\cdots TOp_{xy\_as}\} \rightarrow [TOp_{x\_as}] \\ \{TOp_{x1\_gp/macro} \cdots\cdots\cdots TOp_{xm\_gp/macro}\} \rightarrow [TOp_{x\_gp/macro}] \\ \{TOp_{x1\_gp/wav} \cdots\cdots\cdots TOp_{xk\_gp/wav}\} \rightarrow [TOp_{x\_gp/wav}] \\ \{TOp_{x1\_gp/micro} \cdots\cdots\cdots TOp_{xl\_gp/micro}\} \rightarrow [TOp_{x\_gp/micro}] \\ \{TOp_{x1\_gp/submicro} \cdots\cdots\cdots TOp_{xp\_gp/submicro}\} \rightarrow [TOp_{x\_gp/submicro}] \\ \{TOp_{x1\_fp} \cdots\cdots\cdots TOp_{xr\_fp}\} \rightarrow [TOp_{x\_fp}] \end{array} \right| \tag{19}$$

where:

$\{TOp_{x1\_as} \cdots\cdots\cdots TOp_{xy\_as}\}$,
$\{TOp_{x1\_gp/macro} \cdots\cdots\cdots TOp_{xm\_gp/macro}\}$,
$\{TOp_{x1\_gp/wav} \cdots\cdots\cdots TOp_{xk\_gp/wav}\}$,
$\{TOp_{x1\_gp/micro} \cdots\cdots\cdots TOp_{xl\_gp/micro}\}$,
$\{TOp_{x1\_gp/submicro} \cdots\cdots\cdots TOp_{xp\_gp/submicro}\}$,
$\{TOp_{x1\_fp} \cdots\cdots\cdots TOp_{xr\_fp}\}$ are the set of *y* accuracy parameters, *m* parameters of shape deviation and mutual arrangement of surfaces, *k* parameters of waviness, *l* parameters of roughness, *p* parameters of submicro-roughness, *r* physical and mechanical parameters of the quality of the surface layer, which are provided for the *x-th* functional surfaces;

$[TOp_{x\_as}]$, $[TOp_{x\_gp/macro}]$, $[TOp_{x\_gp/wav}]$, $[TOp_{x\_gp/micro}]$, $[TOp_{x\_gp/submicro}]$, $[TOp_{x\_fp}]$ are limiting values of indicators of accuracy, shape deviation and mutual arrangement of surfaces, waviness, roughness, submicro-roughness, physical and mechanical parameters of surface quality, respectively.

To select or calculate the technological parameters of the technological process, a set of limit values of part quality parameters or its limiting quality parameter selected from the set for the specified *x-th* surface of the part is used:

$$[TOp_{x\_as}], [TOp_{x\_gp/macro}], [TOp_{x\_gp/wav}], [TOp_{x\_gp/micro}], [TOp_{x\_gp\_submicro}], [TOp_{x\_fp}] \rightarrow [TOp_x]. \tag{20}$$

Expression (19) is presented taking into account the material parts'homogeneity as a parameter used for evaluating technological inheritability of their quality parameters for the principle of functionally-oriented design of technological processes in the following form:

$$\left| \begin{array}{l} \{TOp_{x1\_as} \cdots\cdots\cdots TOp_{xy\_as}\} \rightarrow [TOp_{x\_as}] \\ \{TOp_{x1\_gp/macro} \cdots\cdots\cdots TOp_{xm\_gp/macro}\} \rightarrow [TOp_{x\_gp/macro}] \\ \{TOp_{x1\_gp/wav} \cdots\cdots\cdots TOp_{xk\_gp/wav}\} \rightarrow [TOp_{x\_gp/wav}] \\ \{TOp_{x1\_gp/micro} \cdots\cdots\cdots TOp_{xl\_gp/micro}\} \rightarrow [TOp_{x\_gp/micro}] \\ \{TOp_{x1\_gp/submicro} \cdots\cdots\cdots TOp_{xp\_gp/submicro}\} \rightarrow [TOp_{x\_gp/submicro}] \\ \{TOp_{x1\_fp} \cdots\cdots\cdots TOp_{xr\_fp}\} \rightarrow [TOp_{x\_fp}] \end{array} \right| \rightarrow [TOp_x], \tag{21}$$

$$\Updownarrow$$

$$\left| \begin{array}{l} m_{x_0} \rightarrow m_{x_1} \rightarrow \ldots m_{x_k} \rightarrow \ldots \rightarrow m_{x_n}; \\ v_{x_0} \rightarrow v_{x_1} \rightarrow \ldots v_{x_k} \rightarrow \ldots \rightarrow v_{x_n}; \\ A_{x_0} \rightarrow A_{x_1} \rightarrow \ldots A_{x_k} \rightarrow \ldots \rightarrow A_{x_n}; \\ D_{x_0} \rightarrow D_{x_1} \rightarrow \ldots D_{x_k} \rightarrow \ldots \rightarrow D_{x_n} \end{array} \right|$$

where: *k*=1 – blank; *k*=1,...*n* – methods of machining for the *x-th* surfaceof workpiece; $m_{x_0} .. m_{x_n}$; $v_{x_0} .. v_{x_n}$; $A_{x_0} \ldots A_{x_n}$; $D_{x_0} ... D_{x_n}$– the change in the Weibull homogeneity coefficient, the material constant and the material'stechnological damageability of the part during the processing of its *x-th* surface following a rational route of its processing, respectively.

3.2. Development of technological inheritability of parameters for technological processes planning of machine parts manufacturing

Technical conditions of parts and machines generally do not regulate the complete set of the fundamental parameters regarding surface engineering, howeverin most cases are confinedto surface roughness as well as microhardness. A planning stage of the technological processes of parts manufacturing and machine assembly does not always take into account the rational structure of technological operations, cutting modes, progressive processing methods, which are generally chosen to achieve high productivity. At the same time, when processing parts by cutting, material properties that change due to acting loads, high temperatures and harmfull conditions aggressive media, etc. are not sufficiently analyzed.

The increase in the effective application of the principles of object-oriented and functionally-oriented planning technological processes in manufacturing of parts and assembly of machines is attainable by the analysis of degradation of processes related to parts materials at the stage of design and technological preparation and the prediction of their behavior within the life cycle of engineered products. A level of the structural material homogeneity after the technological processing of machine parts is carried out atparticulartechnological steps, performing the operations according to the developed technological routes of surface processingunder specified operating conditions. Herewith, entering the data into the repository takes place both during the design stage, while preparing the technology of production, performing the processing of experimental samples (witness samples) and asmachine parts are manufactured.

This approach needs a thorough investigation related to decerease or loss of the working capacity of particular product at all levels of investigations, starting from the sub-microscopic (atomic-molecular interactions) and ending with the macroscopic.

The entire technological chain “blank –workpiece – final part” is examinedcomprehensively considering allthe important stages as well as substages of the life cycle of mechanical product in order to take into account the principles of technological inheritabilityof the properties and quality parameters. The algorithm designated to planning of the technological routes of the parts’ surfaces machining is based on the technological inheritability of the quality parameters of mechanical engineering objects starting by the manufacturing of the workpiece and ending by the finishing and finishing-strengthening technological operations. The investigation considering the technological inheritability of the quality parameters of machine elementsindicate the dynamics changes in the homogeneity of the material structure after technological processing at particular individual technological steps in accordance with the developed technological routes of surfaces processing aiming to attain the monitored quality parameters of the parts (Fig. 4).

In the common practice related to the material science research, the homogeneity of the part’s material is characterized by the Weibull homogeneity coefficient m or (to a much lesser extent) the coefficient of variation ν. The state of the functional surfaces of machine parts during the manufacturing or operation, while considering the particular material, is analyzed in many studies, taking into account the changes in the Weibull homogeneity coefficient m or the coefficient of variation ν [31,36]. The dynamics of changes in the homogeneity of the surface layer of the parts differ while analyzing the materialsof different physical and mechanical properties. Therefore, to specify the homogeneity of the surface layer of the mechanical parts, other characteristics that determine their relationship with the Weibull homogeneity coefficient m (Fig. 4) must be applied.

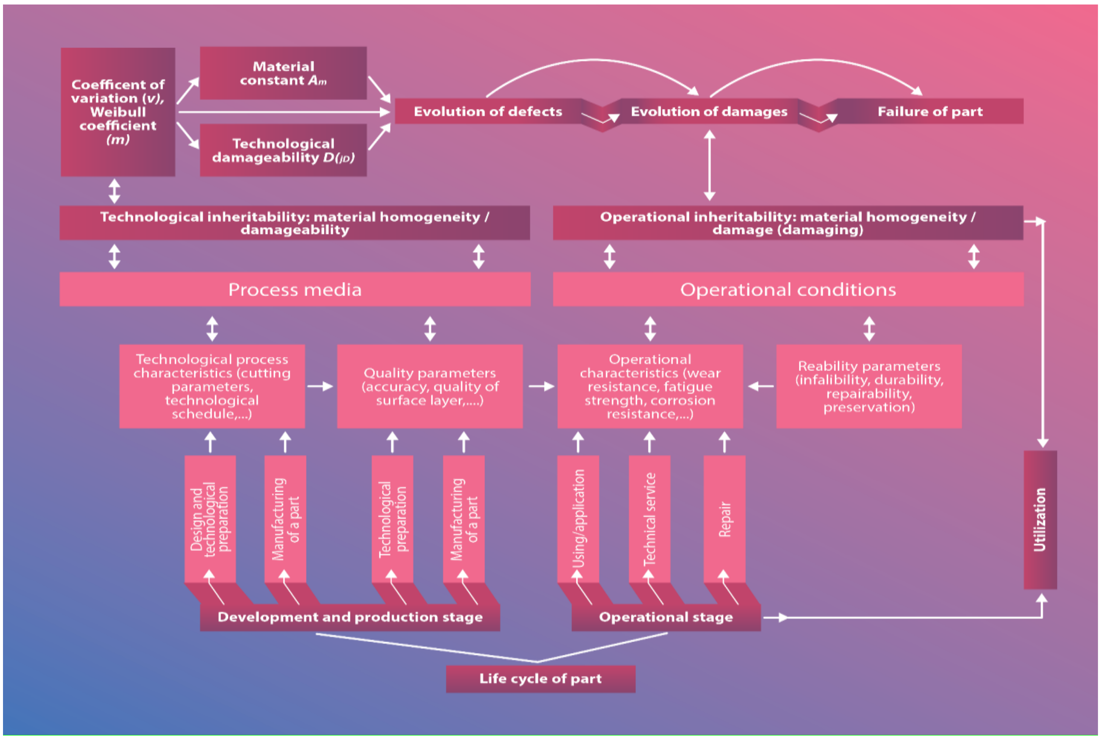

Fig. 4. Part life cycle analysis based on material homogeneity parameters.

A limited number of functioning algorithms have been established for the automated provision of operational characteristics and regulated quality parameters of machine parts to describe the process of technological inheritability for different objects of mechanical engineering properties at the substages and stages in their life cycles within the framework of a synergistic approach. This determines the selection of priority criteria for the estimation of the degradation processes of material properties of parts for the analysis of technological parameters during their manufacturing.

It is suggested that the material homogeneity, defined by certain characteristics, is used as a parameter to evaluate the technological inheritability of parts' surface characteristics after their mechanical processing. From this point of view, homogeneity integrally characterizes the state of the part material after processing of the measurement results using a set of hardness values.

The analysis of physical processes from nanozones to macrozones of machine parts is a characteristic feature of the implementation of the functionally-oriented design principle, depending on the production tasks set. In our research, macrohardness is an integral characteristic of the material in the surface layer of machine parts to estimate the technological inheritability of their quality related features. Analysis of the dynamics of changes in macrohardness determines the search for optimal options for the structure of technological routes for the processing of part surfaces for the implementation of technological support for product subsystems depending on operational requirements.

According to the criterion of homogeneity of materials in the technological chain "blank - workpiece - final part", three variations for the machining of machine parts for the technological inheritability of material properties are implemented:

1) the blank of structurally homogeneous material is transformed into the structurally homogeneous material of the final part at machining processing, heat treatment and plastic deformation of the surface;

2) the blank ofstructurally heterogeneous material provides the structurally heterogeneous material of the final part at machining, heat treatment and plastic deformation of the surface;

3) the blank ofstructurally heterogeneous material provides the structurally homogeneous material of the final part at machining, heat treatment and plastic deformation of the surface after removing the defective surface layer.

The first and second variations provide part quality parameters that are necessary for operating conditions in the process of their technological inheritability of important characteristics without changing the initial state of the blank's material.

The surface of the blank, as a rule, contains pores, shells, and impurities, which determine the structural heterogeneity of the material for the surface layer of mechanical engineering parts as a result of blanks production and technological machining. The structure of the part is formed by the methods of mechanical processing, heat treatment and plastic deformation of the surface. It provides a result of technological inheritability of parts properties from the blank to the final part in the technological stages of the specified operations after removing the defective layer of material. This implements the third variation of technological inheritability of part features.

Based on the principles of the Kachanov-Rabotnov theory [15, 20]:

$$\psi = d\tilde{A}/dA, \tag{22}$$

$$D = 1 - \psi = \left(dA - d\tilde{A}\right)/dA = dA_D/dA, \tag{23}$$

where: D, ψ are damageability and integrity, respectively; dA, dA_D, $d\tilde{A}$ are the investigated area of the material, area of the material without damage as well as area with damage, respectively.

Technological damageability D is estimated by scattering the hardness valuesfollowing Rockwell, Brinell or Vickers according to the dynamics of the change of the Weibull homogeneity coefficient m:

$$D = (m_{matr.} - m_i)/m_{matr.}, \tag{24}$$

where: $m_{matr.}$and m_i denote Weibull homogeneity coefficients m, respectively, determined by the dispersion in the base material hardness as well as in the *i-th* section of the part.

The growth intensity j_D of technological damageability is calculated according to the formula:

$$j_D = (m_{matr.} - m_i)/m_i. \tag{25}$$

Technological damageability D (24) is defined as difference between the Weibull homogeneity coefficients of the matrix (base material) devided by the *i-th* section of the part to the Weibull homogeneity coefficient of the matrix. Whereas the intensity of technological damage growth j_D (25) is interpreted as the difference between the Weibull homogeneity coefficients of the matrix (base material) devided by the *i-th* cross-section of the part with the Weibull homogeneity coefficient in the *i-th* cross-section of the part.

The technological inheritability of parameters of machine parts is analyzed according to the current values m in the investigated cross-sections and the material constant A_m, is calculated using the expression (16), with the unknown distribution of the Weibull homogeneity coefficient m over the thickness (depth) of the part. Having known the distribution of the Weibull homogeneity coefficient m over the thickness (depth) of the part, he technological inheritability of its parameters is estimated by the current values of m in the investigated sections, technological damageability D and the growth intensity j_D, determined by the expressions (24) and (25). The general trend for estimating the homogeneity or damageability of the materials of machine parts is established when the homogeneity of the surface layer of machine parts is used as a criterion to assess the degree of material degradation

The degree of homogeneity of the surface layer material of machine parts is described using the processed values of the Weibull homogeneity coefficient and the coefficient of variation taking into accoungt the dispersion of hardness parameters. In general, the Weibull's homogeneity coefficient m and indicators associated with it: material constant A_m, material D technological damageability of parts and the growth intensity related to the technological damageability j_D are calculated using the results of research specimens processing either chosen from the database for the functional surface machining following the rational route of processing.

The material homogeneity criterion (MHC) is suggested based on the theoretical and experimental analysis (Fig. 5). MHC is described by the parameter of homogeneity of the material of the part, that is used to estimate and analyse the technological inheritability of the parameters of the machined surfaces of the element, and depending on: the Weibull homogeneity coefficient m, the variation coefficient v, the material constant A_m, the technological damageability D as well as the growth intensity j_D.

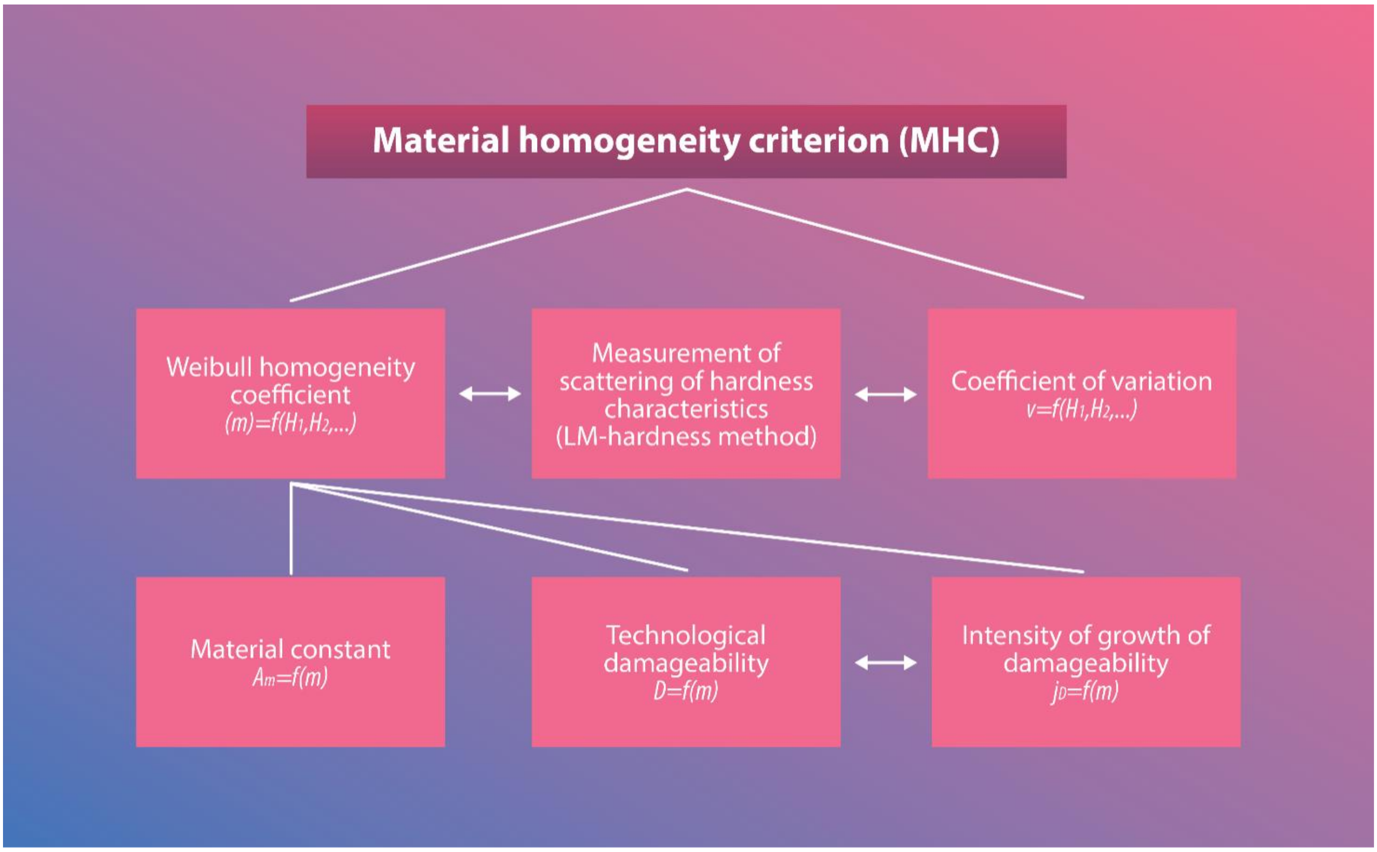

Fig. 5. The structure of the MHC and indicators describing it.

In the general case, the MHC (Fig. 5) is suggested for the analyses of the technological inheritability of the quality features of elements' material at their manufacturing stage with different methods: cutting methods, plastic deformation and determination of the properties of the surface layer using the LM-hardness method, which is determined for each technological step according to a set of indicators, as:

- analysis of a manufacturing step ata given technological operation, with the use ofthe technological inheritability of properties

$$MHC \in [m = f(H_1, H_2\ldots\ldots); \nu = f(H_1, H_2\ldots\ldots); \mathrm{A} = f(m); D = f(m)\,; j_D = f(m)], \quad (26)$$

- evaluation of the technological inheritability of the quality parameters of the mechanical engineering part from the blank to the final part

$$\left|\begin{matrix} m_{x_1} <\ldots m_{x_k} <\ldots< m_{x_n} \to \infty\,; & \nu_{x_1} >\ldots \nu_{x_k} >\ldots> \nu_{x_n} \to 0 \\ A_{x_1} < \cdots A_{x_k} <\ldots< A_{x_n} \to 1\,; & D_{x_1} >\ldots D_{x_k} >\ldots> D_{x_n} \to 0; \end{matrix}\right| \text{for } \mathrm{T}_0 = \textstyle\sum_{k=1}^{n} t_{\mathrm{o\,k}}, \quad (27)$$

- assessmentof the structurally heterohomogeneous state of the material of the surface layersfor the mechanical engineering part

$$m < 10\,; \nu \to 1(100\ \%);\ A_m < 0.878;\ D \to 1, \quad (28)$$

- assessment of the structurally homogeneous state of the material of the surface layersfor the mechanical engineering part

$$m \geq 10;\ \nu \to 0\,; A_m \geq 0.878;\ D \to 0, \quad (29)$$

where: t_{0k} is the machining time at the realization of the *k-th*manufacturing step; T_0 is the total machining time, during which machining is being performed to change the size and form or the state of the certain surface of the mechanical engineering part.

The number of indicators used (26)–(29) is determined by the complexity of the technological tasks performed for various stages of design in order to assess the homogeneity of the material of the part at the specified stage of manufacturing. The Weibull homogeneity coefficient value (m) can be calculated using (26)-(29) with the help of equations (8)-(10), the variation coefficient ν - with equation (11), the material constant A_m – with equation (16), while the technological damageability D as well as its growth intensity j_D – with equations (24) and (25), respectively.

In order to determine the homogeneity of the material of the processed part at a specific stage of its production, the corresponding indicators presented in dependencies (26)-(29) are used. When assessing the complexity of operations, attention is paid to their nature and purpose. The complexity increases with the increase in the precision of the machining of the part, as well as by changing the properties of the material of the part, for example, when applying heat treatment. As a result, the number of evaluated indicators changes. If the evaluation of the homogeneity of the blank material is limited to indicators m and A_m, then a larger number of indicators are used to evaluate the homogeneity of the material of the final part, for example, indicators m, A_m, D, j_D, etc.

4. The results of the experimental analysis and discussion

The results of the carried-out research were tested under real conditions at the manufacturing of the conveyor belt drive drum stepped shaft, which is the main part of this mechanism (Fig. 6). The material of this mechanical engineering part is structural steel EN 37Cr4KD.

Fig. 6. Conveyor belt drive drum shaft.

The type of the blank is a round rolled bar. The mass of the blank is 332.24 kg, its overall dimensions are ∅ 160×2105 mm, the mass of the manufactured part is 243 kg and the material utilization rate is equal to 0.73.

The sequence of machining operations was designed taking into account the tolerance grades of dimensions and the roughness of the shaft surfaces. The technological routes of shaft surfaces machining have been established:

- for ∅ 90h7, ∅ 125h7$_l$, ∅ 125h7$_r$ – rough turning, finish turning, rough grinding, finish grinding;
- for ∅ 148h9$_l$, ∅ 148h9$_r$ – rough turning, finish turning, rough (single) grinding;
- for ∅ 156h14 – rough (single) turning.

The results of the research are presented in Table.

Table. Changes in the main indicators of the material homogeneity criterion at the machining of conveyor drive shaftsurfaces.

Machiningoperations	Being processed surfaces and managed indicators									
	∅ 90h7					∅ 125h7$_l$				
	m	$A_m(m)$	$D(m)$	$j_D(m)$	ν (%)	m	$A_m(m)$	$D(m)$	$j_D(m)$	ν (%)
	Tendency to damageability↑					Tendency to damageability↑				
Blank	6.12	0.815	0.983	56.19	18.77	6.13	0.815	0.982	56.10	17.87
Rough turning	35.37	0.962	0.899	8.895	3.24	34.02	0.961	0.903	9.288	3.32
Finish turning	98.82	0.986	0.718	2.542	1.15	91.93	0.985	0.737	2.807	1.23
Rough grinding	239.72	0.994	0.315	0.46	0.49	215.62	0.994	0.384	0.623	0.53
Finish grinding	333.89	0.996	0.046	0.048	0.34	344.59	0.996	0.015	0.016	0.33
	Tendency to homogeneity of the material structure↓					Tendency to homogeneity of the material structure↓				
Machining operations	Being processed surfaces and managed indicators									
	∅ 148h9$_l$					∅ 156h14				
	m	$A_m(m)$	$D(m)$	$j_D(m)$	ν (%)	m	$A_m(m)$	$D(m)$	$j_D(m)$	ν (%)
	Tendency to damageability↑					Tendency to damageability↑				
Blank	9.67	0.875	0.972	35.194	11.98	11.46	0.892	0.967	29.541	9.63
Rough turning	40.89	0.967	0.883	7.56	2.74	32.06	0.959	0.908	9.917	3.59
Finish turning	100.43	0.986	0.713	2.485	1.13					
Rough grinding	206.46	0.993	0.41	0.695	0.55					
Finish grinding										
	Tendency to homogeneity of the material structure↓					Tendency to homogeneity of the material structure↓				
Machining operations	Being processed surfaces and managed indicators									
	∅ 148h9$_r$					∅ 125h7$_r$				
	m	$A_m(m)$	$D(m)$	$j_D(m)$	ν (%)	m	$A_m(m)$	$D(m)$	$j_D(m)$	ν (%)
	Tendency to damageability↑					Tendency to damageability↑				
Blank	11.14	0.889	0.968	30.418	10.10	6.10	0.814	0.983	56.377	18.80
Rough turning	37.69	0.965	0.892	8.286	2.96	33.81	0.961	0.903	9.352	3.34
Finish turning	93.54	0.985	0.733	2.742	1.22	88.03	0.985	0.748	2.976	1.28
Rough grinding	198.23	0.993	0.434	0.766	0.57	218.55	0.994	0.376	0.601	0.52
Finish grinding						336.86	0.996	0.038	0.039	0.34
	Tendency to homogeneity of the material structure↓					Tendency to homogeneity of the material structure↓				

Taking into account the large mass and dimensions of the shaft, the portable hardness tester TD-42 was used to measure hardness of surface layers of the part. A standard Brinell hardness measurement method was used.

During the experimental analysis, the homogeneity of the material of the processed part was analyzed using current values of the coefficient of variation ν and Weibull homogeneity coefficient m as per formulas (11), (8)–(10). Subsequently, both the constant A_m and technological damageability D of the material of the part were calculated and also the growth intensity j_D of the technological damageability. A change in the parameters of the MHC in the technological chain "blank-workpiece-final part" occurs during the production of the shaft blank according to the principle of technological inheritability of its quality parameters.

The initial blank has characteristic of a low homogeneity of the material surfaces, that is approved by both the low values of the Weibull homogeneity coefficients (m=6.12-11.46) and high values of the coefficient of variation (ν=9.63-18.77%), and the average value of the material constant A_m is equal to 0.85 < 0.878, which corresponds to the state of structurally heterogeneous material. The tendency to damage the surface layers of the material for the blank is high, and this is confirmed by the technological damageability values D=0.967-0.983, which are close to unity. In this case, the growth intensity of technological damageability j_D is 29.541-56.377.

An increase in the homogeneity of the layers of the workpiece surface is obtained by removal the defective layer already after rough turning. This is shown by the increase in the values of the Weibull homogeneity coefficients (m=32.06-40.89) and the decreasein the values of the variation coefficients (ν=2.74-3.59%). Removal of the defective layer provides a transition from a structurally heterogeneous state of the blank material to a structurally homogeneous layer of the processed workpiece, improving the values of the material constant A_m=0.959-0.967 > 0.878. Moreover, the technological damageability values decrease from D=0.967-0.983 (for the initial blank) to D=0.883-0.908 (after rough turning).

Finishing turning after rough turning provides further increasing of Weibull homogeneity coefficients (m=88.03-100.43), material constants (A_m =0.985-0.986), and reduction of variation coefficients (ν=1.13-1.28 %). Herewith, the dispersion of absolute value and technological damageability decreases (D=0.713-0.748). The intensity of technological damageabilitygrowthdecreases from j_D=29.541-56.377 (for blank) to j_D=2.485-2.976 (after finishing turning).

Grinding of the shaft surfaces includes a rough grinding (for ∅ $148h9_l$and ∅ $148h9_r$) and double machining: rough grinding and finishing grinding (for ∅ 90h7, ∅ $125h7_l$and ∅ $125h7_r$).

A further increasing of the homogeneity of the machined surfaces is ensured by rough grinding of the shaft necks ∅ 148h9, which is confirmed by the increasein the Weibull homogeneity coefficients (m=198.23-206.46) and the material constant (A_m =0.993), as well as decrease in the coefficients of variation to ν=0.55-0.57%. At the same time, the absolute values and dispersion of technological damageability decrease significantly (D=0.41-0.434) with the intensity of its growth j_D=0.695-0.766.

The final grinding of the shaft necks of dimensions∅ 90h7, ∅ 125h7 provides the highest homogeneity of the processed surfaces. This is confirmed by high values of Weibull homogeneity coefficients (m=333.89-344.59), stabilization of the material constant (A_m =0.996) and variation coefficients (ν=0.33-0.34%). The values of technological damageability (D=0.015-0.046) and its growth intensity j_D=0.016-0.048 are close to zero, which indicates the general tendency to the material homogeneity of the surface layers of the shaft.

The homogeneity of the material is a very important factor in the machining of parts, as it directly affects the machining process and the further operation of the final product. Inhomogeneity or variations in material composition and different hardness lead to uneven cutting forces during machining and faster wear of cutting tools. Due to the non-uniform properties of the material, residual stresses are often formed in the parts after processing, and there is a possibility of deformations. The homogeneous structure of the material reduces these stresses and, at the same time, the final distortion or deformation of the part. In addition, the homogeneity of the structure ensures that the cutting force and heat generation during machining are the same, which improves the surface smoothness of the part and results in better dimensional accuracy. This is especially important in the production of precision parts, where relatively small tolerances and dimensional stability are required. Establishing homogeneity criteria enables engineers to optimize cutting parameters and ensure that the final product meets specified operational requirements.

According to the theory of technical systems, the technological inheritability of product parameters at their machining is carried out due to the transformation of a set of initial information flows through a set of internal information flows and connections of a material, energy nature into a set of initial information flows), which provide performance characteristics and reliability indicators of the product while meeting the requirements regarding the accuracy and quality of the surface layer of the functional surfaces of machine parts.

The technological inheritability of product quality parameters is provided by the characteristics of its material and surface engineering indicators of the product. According to the accepted hypothesis, the homogeneity of the material is defined as a parameter for the analysis of technological inheritability based on the assessment of the degradation of the material properties for the rational selection of the blank and the design of the rational structure of the technological route for machining of executive surfaces of parts at manufacture of products.

It established that the analysis of the degree of degradation of the parts material at their machining according to the indicators of its homogeneity is an effective approach in technological routes planning at machining of the functional surfaces of products. This technique is an alternative to the traditional selection of technological machining methods based on the parameters of accuracy and quality of surface layers.

The parameters of accuracy, quality of the surface layer, operational characteristics and reliability indicators of machine parts regulated by technical conditions are formed at machining of the blanks using technological inheritaability from the first to the *k-th* technological steps and operations in compliance with the requirements for changing the indicators of the material homogeneity criterion developed by us from the blank to the part: Weibull homogeneity coefficient – $m_{x_1} <\ldots m_{x_k} <\ldots< m_{x_n} \to \infty$; coefficient of variation – $\nu_{x_1} >\ldots \nu_{x_k} >\ldots> \nu_{x_n} \to 0$; material constant – $A_{x_1} < \ldots A_{x_k} <\ldots< A_{x_n} \to 1$; technological damageability – $D_{x_1} > \ldots D_{x_k} >\ldots> D_{x_n} \to 0$; the intensity of its growth – $j_{D_{x_1}} > \ldots j_{D_{x_k}} >\ldots> j_{D_{x_n}} \to 0$.

In addition, the structural inhomogeneity of the material considered at the macro-, micro-, and sub-micro levels in the manufacture of machine parts is determined by the chemical composition of the material, the blank production, the presence of macrodefects (inclusions, pores, shells, etc.) after manufacturing operations and technological treatments.

The hypothesis of the possibility of implementing three options for the technological inheritabiity of material properties at the macrolevel has been put forward and confirmed. The first and second options provide the quality parameters of the product necessary for operating conditions using their technological inheritability without changing the initial state of the blank material. The third option ensures the transformation of the structurally heterogeneous material of the blank after removing its defective layer into the structurally homogeneous material of the finished part.

A priority direction of further research is the development of a subsystem for the analysis of technological inheritability of parts properties for the analysis of PSPAS-system (Product Shaping/Processing Analysis System) as an important element of CAF-system (Computer Aided Forming system). This will be especially important for the technological provision of operational characteristics and reliability indicators of machine parts operating under conditions of power load and intensive wear.

5. Conclusions

Presented development of functionally-oriented manufacturing technologies for mechanical parts is considered by the systematic approach of theoretical and experimental techniques and computer modeling of rational technological processesincluding the technological inheritability in the technological chain "blank-workpiece-final part".

The technological inheritability of the surface layer properties in made of steel parts during their processing is important to ensure the transformation of the structurally heterogeneous material of the blanks and attain the structural homogeneouty of the final parts‘ material. This is ensured by increasing the Weibull homogeneity coefficients *m* from 6.12-11.46 (after blanks manufacturing) to 198.23-344.59 (resulted by a different technique of grinding) and a decrease in the coefficients of variation ν from 9.63-18.77% (after blanks manufacturing) up to 0.33-0.57% (resulted by different grinding technique applied).

The material constant $A_m$of the part in the technological chain "blank-workpiece-final part" showed the step-by-step increase – the initial value was equal to 0.814 (after blank manufacturing), whereas the final value reached 0.966 (after final grinding) during the manufacturingof the steel shaft. Moreover, the scattering of the material constant A_m values is higher after blanks manufacturing and rough-cut technological processing, later stabilizing these parameters for final technological treatments. This behavior indicates a higher homogeneity of the material structure after finishing, if compainring to the rough-cut techniques of surface treatments and provides possibility to define practical recommendations to be applied while planning optimal technological routes for the surface processing.

It is worthy to note, that technological damageability *D* decreases from 96.7-98.3% (after blanks manufacturing) to 1.5-43.4% (after different grinding), resulting the structurally heterogeneous material (steel blanks) change into structurally homogeneous material (final parts). The material homogeneity improved from blank to final part into 2.23-65.46 times in accordance with the certain technological routes.

The developed technique may be applicable for the dynamic analysis of material homogeneity related changes ofmachine parts resulted by mechanical processing, heat treatment and further operation.

In order to implement the developed method in mechanical engineering production on a larger scale, the complimentary analysis considering other materials, mechanical engineering parts of different classes and various technological treatments is required.

Acknowledgment

The presented research is a part of ongoing project "Comprehensive system of functional-oriented planning of machining difficult-to-cut materials for the military-industrial complex (Komplekssys)", which is funded by the Research Council of Lithuania and the Ministry of Education and Science of Ukraine under the Lithuanian–Ukrainian Cooperation Programme in the Fields of Research and Technologies (Grant No. S-LU-22-6).

References

1. Abdelbary A. Extreme Tribology. Fundamentals and Challenges, 1st ed., CRC Press 2021; 332p, https://doi.org/10.1201/9780429448867-1
2. Abrão AM, Ribeiro JLS, Davim JP. Surface Integrity. In: Davim, J. (eds) Machining of Hard Materials. Springer-Verlag, London 2011; 115-141, https://doi.org/10.1007/978-1-84996-450-0_4.
3. Aftanaziv IS, Shevchuk LI, Strutynska LR, Strogan OI.Vibrational-centrifugal surface strengthening of drill and casing pipes.Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu 2018; 5: 88–97, DOI: 10.29202/nvngu/2018-5/7.
4. Andrych-Zalewska M, Chlopek Z, Pielecha J, Merkisz J. Investigation of exhaust emissions from the gasoline engine of a light duty vehicle in the Real Driving Emissions test. Eksploatacja i Niezawodność – Maintenance and Reliability 2023; 25(2), https://doi.org/10.17531/ein/165880.
5. Bazaluk O, Dubei O, Ropyak L, Shovkoplias M, Pryhorovska T, Lozynskyi V. Strategy of compatible use of jet and plunger pump with chrome parts in oil well. Energies 2022; 15(1): 83, https://doi.org/10.3390/en15010083.
6. Bazaluk O, Velychkovych A, Ropyak L, Pashechko M, Pryhorovska T, Lozynskyi V. Influence of heavy weight drill pipe material and drill bit manufacturing errors on stress state of steel blades. Energies 2021; 14(14): 4198, https://doi.org/10.3390/en14144198.
7. Bembenek M, Prysyazhnyuk P, Shihab T, Machnik R, Ivanov O, Ropyak L. Microstructure and wear characterization of the Fe-Mo-B-C—based hardfacing alloys deposited by flux-cored arc welding. Materials 2022; 15(14): 5074, https://doi.org/10.3390/ma15145074.
8. Bertsche B. Reliability in Automotive and Mechanical Engineering. Berlin Heidelberg: Springer-Verlag 2008; 492p, https://doi. org/10.1007/978-3-540-34282-3.
9. Birolin, A. Quality and Reliability of Technical Systems: Theory, Practice, Management. 2nd Edition. Springer-Verlag Berlin Heidelberg GmbH 1997; 502p, https://doi.org/10.1007/978-3-642-97983-5.
10. Borucka A. Three-state Markov model of using transport means, Business Logistics in Modern Management, 2018; 18, 3-19, ISSN 1849-5931.
11. Demminger C, Mozgova I, Quirico M, Uhlich F, Denkena B, Lachmayer R, Nyhuis P. The consept of technical inheritance in operation: Analysis of the information flow in the life cycle of smart product. Procedia Technology 2016; 26: 79-88, doi:10.1016/j.protcy.2016.08.012.
12. Denkena B, Mörke T, Krüger M, Schmidt J, Boujnah H, Meyer J, Gottwald P, Spitschan B, Winkens M. Development and first

applications of gentelligent components over their lifecycle. CIRP Journal of Manufacturing Science and Technology 2014; 7(2): 139-150, https://doi.org/10.1016/j.cirpj.2013.12.006.

13. Grzesik W. Prediction of the functional performance of machined components based on surface topography: State of the art. Journal of Materials Engineering and Performance 2016; 25: 4460–4468, https://doi.org/10.1007/s11665-016-2293-z.
14. Hagen J, Buth L, Haupt J, Cerdas F, Herrmann C. Live LCA in learning factories: real time assessment of product life cycles environmental impacts. Procedia Manufacturing 2020; 45: 128-133, 10.1016/j.promfg.2020.04.083.
15. Haque MS, Stewart CM. Comparative analysis of the sin-hyperbolic and Kachanov-Rabotnov creep damage models. International Journal of Pressure Vessels and Piping 2019; 171: 1-9, https://doi.org/10.1016/j.ijpvp.2019.02.001.
16. Hashemi SH. Strength-hardness statistical correlation in API X65 steel. Materials Science & Engineering A 2011; 528(3): 1648-1655, https://doi.org/10.1016/j.msea.2010.10.089.
17. Hubka V,Eder WE. Theory of Technical Systems: A Total Concept Theory for Engineering Design. Springer-Verlag, New York 1988; 278p, http://dx.doi.org/10.1007/978-3-642-52121-8.
18. Ivanov V, Dehtiarov I, Pavlenko I, Kosov M, Hatala M. Technological Assurance and Features of Fork-Type Parts Machining. In: et al. Advances in Design, Simulation and Manufacturing II. DSMIE 2019. Lecture Notes in Mechanical Engineering. Springer, Cham 2020; 114-125, doi: 10.1007/978-3-030-22365-6_12.
19. Ivanov V, Dehtiarov I, Pavlenko I, Kosov I, Kosov M. Technology for complex parts machining in multiproduct manufacturing. Management and Production Engineering Review 2019; 10(2): 25-36, DOI: 10.24425/mper.2019.129566
20. Kachanov LM. Rupture time under creep conditions. International Journal of Fracture 1999; 97: 11-18, https://doi.org/10.1023/A:1018671022008.
21. Khadem M, Penko, O V, Yang H-K, Kim D-E. Tribology of multilayer coatings for wear reduction: A review. Friction 2017; 5(3): 248–262, https://doi.org/10.1007/s40544-017-0181-7.
22. Kharchenko VV, Katok OA, Kravchuk RV, Sereda AV, Shvets VP. Analysis of the methods for determination of strength characteristics of NPP main equipment metal from the results of hardness and indentation measurements. Procedia Structural Integrity 2022; 36: 59-65, 10.1016/j.prostr.2022.01.003.
23. Khonsari MM, Booser EM. Applied Tribology: Bearing Design and Lubrication (Tribology in Practice Series), 3rd ed. Wiley 2017; 672p., https://doi.org/10.1007/978-0-85729-694-8
24. Kołowrocki K, Soszynska-Budny J. Reliability and Safety of Complex Technical Systems and Processes: Modeling—Identification—Prediction— Optimization. Springer-Verlag, London Limited 2011; 419p.
25. Kopei V, Onysko O, Odosii Z, Pituley L, Goroshko A. Investigation of the influence of tapered thread profile accuracy on the mechanical stress, fatigue safety factor and contact pressure. In: Karabegovič, I. (ed) New Technologies, Development and Applications IV, Lecture Notes in Networks and Systems, vol 233. Springer Publishing 2021; 177-185, DOI: 10.1007/978-3-030-75275-0_21.
26. Kopylov V, Kuzin O, Kuzin N. Improving contact durability of polycryctalline systems by controlling the parameters of large-angle grain boundaries. Eastern-European Journal of enterprise technologies 2019; 5/12(101): 14-22, https://doi.org/10.15587/1729-4061.2019.181441.
27. Kozłowski E, Borucka A, Świderski A, Skoczyński P. Classification Trees in the Assessment of the Road–Railway Accidents Mortality. Energies 2021; 14(12):3462, https://doi.org/10.3390/en14123462.
28. Kragelsky IV, Alisin VV. Tribology -Lubrication, Friction, and Wear. Tribology in Practice Series, 1st ed. John Wiley & Sons Ltd 2005; 948p.
29. Krimpenis A,Vosniakos G.-C. Rough milling optimisation for parts with sculptured surfaces using genetic algorithms in a Stackelberg game. Journal of Intelligent Manufacturing 2009; 20: 447-461, DOI 10.1007/s10845-008-0147-8.
30. Kusyi Y, Stupnytskyy V, Onysko O, Dragašius E, Baskutis S, Chatys, R. Optimization synthesis of technological parameters during manufacturing of the parts. Eksploatacja i Niezawodność – Maintenance and Reliability 2022; 24(4): 655–667, https://doi.org/10.17531/ein.2022.4.6
31. Kusyi Y,M, Kuk AM. Investigation of the technological damageability of castings at the stage of design and technological preparation of the machine Life Cycle. Journal of Physics: Conference Series 2020; 1426(1): 012034, DOI: 10.1088/1742-6596/1426/1/012034.

32. Kwak K, Mine Y, Morito S, Ohmura T, Takashima K. Correlation between strength and hardness for substructures of lath martensite in low- and medium-carbon steels. Materials Science & Engineering A 2022; 856: 144007, https://doi.org/10.1016/j.msea.2022.144007.
33. Kuzin N, Meshcheryakova T, Kuzin O, Kurileva E, Gordinskaya N. The use of mathematical and computer modeling in solving the problems of rail transport expert examination. Journal of Applied Mathematics and Computational Mechanics 2016; 15(4): 93-98, DOI: 10.17512/jamcm.2016.4.10.
34. Latinovic T, Barz C, Vadean AP, Sikanjic G, Sikman L. Adaptive intelligence system for a predictive process for the Industry 4.0 in Tobacco factory. Journal of Physics: Conference Series 2020; 1426: 012019, DOI:10.1088/1742-6596/1426/1/012019.
35. Latinovic T, Preradović D, Barz CR, Vadean AP, Todić M. Big Data as the basis for the innovative development strategy of the Industry 4.0. IOP Conf. Series: Materials Science and Engineering 2019; 477:012045, doi:10.1088/1757-899X/477/1/012045.
36. Lebedev AA, Makovetskii IV, Muzyka NR, Volchek NL, Shvets VP.Assesment of damage level in materials by the scatter of elastic characteristics and static strength. Strength of Materials 2006; 38(2):109-116, https://doi.org/10.1007/s11223-006-0022-9.
37. Lee H-h, Lee S, Park J-K, Yang M. Friction and wear characteristics of surface-modified titanium alloy for metal-on-metal hip joint bearing. International Journal of Precision Engineering and Manufacturing 2018; 19(6): 917–924,10.1007/s12541-018-0108-x.
38. Montinaro N, Cerniglia D, Pitarresi G. Defect detection in additively manufactured titanium prosthesis by flying laser scanning thermography. Procedia Structural Integrity 2018; 12: 165-172, DOI: 10.1016/j.prostr.2018.11.098.
39. Mozgova, I, Barton S, Demminger C, Miebach T, Taptimthong P, Lachmaye, R, Nyhuis P, Reimche W, Wurz MC. Technical inheritance: Information basis for the identification and development of product generations. In: Maier, A. et al. (eds). Proceedings of the 21st International Conference on Engineering Design (ICED17), Vancouver, Canada, 21-25 August, 2017; 6: 91-100.
40. Murakami S. Continuum Damage Mechanics: A Continuum Mechanics Approach to the Analysis of Damage and Fracture. Springer, Dordrecht/Heidelberg/London/New York 2012; 432p.
41. Muzyka NR, Shvets VP, Boiko AV. Procedure and instruments for the material damage assessment by the LM-Hardness method on the in-service scratching of structure element surfaces. Strength of Materials 2020; 52(3):432-439,DOI 10.1007/s11223-020-00195-6.
42. Orman LJ. Enhancement of pool boiling heat transfer with pin-fit microstructures, Journal of Enhanced Heat Transfer 2016; 23(2), 137-153, DOI: 10.1615/JEnhHeatTransf.2017019452
43. Orman LJ. Boiling heat transfer on meshed surfaces of different aperture, Proc. of Int. Conf. on Application of Experimental and Numerical Methods in Fluid Mechanics and Energetics. AIP Conference Proceedings 2014; 1608; 169-172. DOI: 10.1063/1.4892728
44. Panda S, Sarangi M, Roy Chowdhury SK. An analytical model of mechanistic wear of polymers. Journal of Tribology 2018; 140(1): 011609, https://doi.org/10.1115/1.4037136
45. Papagianni Z, Vosniakos, G.-C.2022. Surface defects detection on pressure die Castings by machine learning exploiting machine vision features. In et al. Advances in Design, Simulation and Manufacturing V, Lecture Notes in Mechanical Engineering. Springer International Publishing 2022; 51–61, DOI: https://doi.org/10.1007/978-3-031-06025-0_6.
46. Pryhorovska T, Ropyak L. Machining error influence on stress state of conical thread joint details, Proceedings of the 8th International Conference on Advanced Optoelectronics and Lasers (CAOL) 2019; 493-497, 10.1109/CAOL46282.2019.9019544.
47. Psarommatis F, May G. A practical guide for implementing Zero Defect Manufacturing in new or existing manufacturing systems. Procedia Computer Science 2023; 217: 82-90, 10.1016/j.procs.2022.12.204.
48. Ropyak LY, Makoviichuk MV, Shatskyi IP, Pritula IM, Gryn LO, Belyakovskyi VO. Stressed state of laminated interference-absorption filter under local loading, Functional Materials 2020; 27(3): 638-642, doi: https://doi.org/10.15407/fm27.03.638.
49. Ropyak LY, Pryhorovska TO, Levchuk KH. Analysis of materials and modern technologies for PDC drill bit manufacturing. Progress in Physics of Metals 2020; 21(2): 274–301, DOI: 10.15407/ufm.21.02.274.
50. Ropyak LY, Velychkovych AS, Vytvytskyi, VS, Shovkoplias MV. 2021. Analytical study of „crosshead - slide rail“ wear effect on pump rod stress state. Journal of Physics: Conference Series 2021; 1741(1): 012039, DOI: 10.1088/1742-6596/1741/1/012039.
51. Shihab T, Prysyazhnyuk P, Semyanyk I, Anrusyshyn R, Ivanov O, Troshchuk L. 2020. Thermodynamic approach to the development and selection of hardfacing materials in energy industry. Management Systems in Production Engineering 2020; 28(2): 84-89, https://doi.org/10.2478/mspe-2020-0013.
52. Shvets’ VP, Muzyka MR, Makovets’kyi IV, Bulakh PO. In-service monitoring of the current switch metal condition. Strenght of

Materials 2011; 43(1): 73-76, https://doi.org/10.1007/s11223-011-9269-x.

53. Stupnytskyy V. Features of functionally-oriented engineering technologies in concurrent environment. International Journal of Engineering Research & Technology 2013; 02(09): 1181–1186, DOI: 10.17577/IJERTV2IS90435.
54. Szymczak T, Kowalewski ZL. Strength tests of polymer-glass composite to evaluate its operational suitability for ballistic shield plates. Eksploatacja i Niezawodność – Maintenance and Reliability 2020; 22(4): 592-600, http://dx.doi.org/10.17531/ein.2020.4.2.
55. Vlagkoulis D, Vasileiou A, Vosniakos G.-C.A study on casting of structural mesh-like metal parts. IOP Conf. Series: Materials Science and Engineering 2021; 1037:012017, DOI 10.1088/1757-899X/1037/1/012017.
56. Zhang X, Hao Y, Shangguan H, Zhang P, Wang A. Detection of surface defects on solar cells by fusing Multi-channel convolution neural networks. Infrared Physics and Technology 2020; 108: 103334, https://doi.org/10.1016/j.infrared.2020.103334.