Development of the fundamental diagram of the formation and transformation of the products properties during their manufacturing

Y M Kusyi, V V Stupnytskyy, A M Kuk and V G Topilnytsky

1Lviv Polytechnic National University, Mechanical Engineering Department, 12, Stepan Bandera str., Lviv, 79013, Ukraine
2Lviv Polytechnic National University, Department of Designing and Operation of Machines, 12, Stepan Bandera str., Lviv, 79013, Ukraine

E-mail: jarkym@ukr.net

Abstract In object-oriented technologies of mechanical engineering production the step-by-step execution of interconnected design stages of technological process of product manufacture is used. A systematic approach to research and qualitative modelling of real physical processes, taking into account the operational characteristics of products and machines at all levels of research is ignored. As a rule, the object-oriented technological processes do not track the change of the products properties during their manufacture from the position of technological inheritability for all stages and substages of the Life Cycle Support of Product. Therefore, the development of scientific and applied principles of technological inheritability of quality parameters to provide the operational characteristics of products in the design of function-oriented technologies is a priority item of modern mechanical engineering. The structure of functional-oriented technology is closely related to the stages and substages of Life Cycle Support of Product. From the standpoint of continuous damage mechanics, Life Cycle Support of Product is considered to be a single process of exhaustion of the material plasticity margin under the influence of certain load modes in accordance with the technological inheritance of the product properties. The basic chart of the formation and transformation of the products properties from the point of view of mechanics of technological inheritability is developed. This chart, in contrast to previous research in this area, takes into account the significant impact of the stage of blanks manufacture in the technological process structure on the formation of technological parameters and operational characteristics of products.

1. Statement of the problem
The quality parameters Quality parameters of mechanical engineering products are characterized by their dimensional accuracy, surface layer quality parameters, operational characteristics and reliability indicators. Providing products quality parameters is a wide concept that is closely related to the substages and stages of the Life Cycle Support of Product (see Figure 1) [1-5].

The technological process has a direct and decisive influence on the quality parameters of mechanical engineering products starting from blank production to finishing technological operations of product manufacture (see Figure 1) [1], [5]. To provide quality parameters, new approaches that are implemented in modern engineering through the introduction of PLM (Product Life Cycle Management) – concepts are required.
Figure 1. Relationships between parameters of technological process, surface quality parameters, operational characteristics and reliability indicators

The PLM concept is a solid foundation for the successful development and launch of new products on the modern market. It effectively combines information and people in order to organize their common work [1].

The PLM concepts represent a system of Life Cycle Support of Product with the development of the functional-oriented technologies by means of parallel engineering [1], [5].

2. Literature survey

A step-by-step execution of interconnected stages of planning the rout of product manufacture is provided in traditional automated systems of technological preparation of the mechanical engineering production. The structure of the technological route of product processing is developed on the basis of initial data obtained from the designer. The structure of the technological process is adjusted and agreed in accordance with the functional capabilities of the existing technological environment. The minimum technological cost of product manufacture with the maximum productivity of the main technological equipment without functional analysis of the operational characteristics is usually a criterion for optimization, when choosing a rational variant of the technological process. This technological process is called object-oriented [6-8]. Modern technologies of mechanical engineering require providing the specified operational characteristics of products in compliance with the parameters of accuracy and quality of the surface layers of their executive surfaces in contrast to achieving the minimum technological cost with maximum productivity in case of classical engineering.

The production experience of mechanical engineering enterprises shows that there is a complex dependence of operational properties and quality parameters of the final product. A designer or automated CAD / CAE system, based on the service purpose of the machine / product, develops a design of a specific product, performing only a simplified analysis of the stress-strain state of the product, and assigns technically sound standards of the accuracy and quality parameters of the surface layer, as well as the mutual location of executive surfaces without analysis of real operating conditions with the involvement of thoroughly developed mathematical models [6-8].

Modern development of applied mechanics shows that the technological support of the main operational characteristics of the product (strength, wear resistance, fatigue strength, etc.) require a systematic approach, which consists not only in investigation of real physical processes at all levels: submicroscopic, microscopic and macroscopic, but also their step-by-step tracking at all stages and
substages of Life Cycle Support of Product from the standpoint of technological inheritability. Technological inheritability is the process of transferring the object properties from previous technological operations to the subsequent ones. Preservation of these properties in the object is called technological inheritance. According to this approach, the system principle of realization of the life cycle of a mechanical engineering product from the point of view of technological inheritability requires a direct connection between technological preparation of production and operation stage with not step-by-step, but parallel, coordinated work of the designer and technology [8].

Therefore, the development of the scientific and applied principles of technological inheritability of the quality parameters to provide the operational characteristics of products when designing the functional-oriented technologies is topical for Life Cycle Support of Product. Functional-oriented technological process (FOTP) is a technological process that is directed at maintaining the most effective operational characteristics of the product with observance of the accuracy and quality parameters of the product surface layer, appointed by the designer. The solution to this problem is possible by means of automated process control and careful analysis of the whole production chain from the standpoint of technological inheritability due to the system integrated software products CAD / SAE / CAPP / CAM. The design and technological preparation of production in order to achieve the maximum positive result in the customer-manufacturer chain is intensified during the FSTP implementation [8].

From the point of view of continuous damage mechanics, the Life Cycle of Product is considered to be the only process of exhaustion of the metal plasticity margin under the influence of certain loading modes in accordance with the technological inheritability of product properties at all stages and substages of its Life Cycle Support of Product (see Figure 2) [9].

![Figure 2](chart.png)

**Figure 2.** A classical chart of formation and transformation of properties of the surface layer using positions of technological inheritance mechanics

The main stages of Life Cycle Support of Product (from manufacture to failure of the product) are: blank production, cutting process, finishing or finishing-hardening operations, stages of fatigue strength and fatigue crack resistance under loading (see Figure 2) [9].
The initial data of classical research are: strength curve $\sigma_i = \sigma_i(\varepsilon_i)$, limit plasticity curve $\Lambda_p = \Lambda_p(\Pi)$, fatigue strength diagram $V_{dur} = V_{dur}(K)$. The main assumption is that the blank metal is not hardened in the initial state, the degree of deformation $\Lambda_\Sigma = 0$, the degree of the plasticity margin exhaustion $\varphi_\Sigma = 0$ and the tensor of residual stress $[T_{\sigma_{res.}}] = 0$ (see Figure 2).

Assumptions about zero deformation degree, plasticity margin exhaustion degree and the absence of residual stresses before the first cutting operation are often far from reality, because before cutting there is a certain process of blank production.

The influence of operations at the blanking stage on the technological inheritability of the product quality parameters is still insufficiently taken into account. The structure and properties of the blanks must be analysed in close combination with the metal inheritance, starting with its liquid state. About 75% of the metal properties are formed during pouring and curing of the alloy at cooling. Only 25% of the properties are transferred to the blank during its production [1].

However, the process of forming the surface quality parameters of the product, its operational characteristics and reliability indicators at the stage of its creation as well as the process of the product fracture at its operation stage require joint theoretical and experimental researches.

3. Research aim and the object of researches
The aim of the research is to develop a basic diagram of the formation and transformation of the products properties during their manufacturing from the blank to the final product by means of technological inheritability mechanics.

The object of researches is the Life Cycle Support of Product from the blank to the final part.

4. Research methods
4.1. Analysis of the chart of formation of qualitative parameters of technological process
Consider the chart of the formation of product quality parameters during technological process, which consists of $n + 1$ consecutive operations - from the blank production (0) to the final operation (n) (see Figure 3) [10].

![Figure 3. A chart of formation of technological process quality parameters](image)

The initial parameters for the implementation of the technological process is a set of values $Y_{0i}, Y_{02}, ..., Y_{0j}$. M of the output parameters $X_1, X_2, ..., X_m$ must be provided as a result of that technological process according to the technical requirements. Probability $P_0(t)$ characterizes the probability of providing technical requirements for the blanking operation of the technological process. The probability $P(t)$ (output of any of the parameters outside the tolerance for a given period t = T) refers to the technical requirements of this process. The formation of the initial parameters occurs as a result of sequential processing of the blank, and for each operation, as a rule, their initial
parameters are assigned, which must be provided as a result of technological transitions of this technological operation (see Figure 3).

The regularities of formation of the initial parameters of all technological process have certain features [10]:

1. The final (finishing and finishing-hardening) operations have the most important influence on the formation of initial parameters, while the parameters controlled in intermediate operations, as a rule, change and their value does not play a significant role (parameters of group I, see Figure 3). The characteristics of the material, which are the initial parameters of the technological process, are usually the exceptions, but they greatly determine its final properties.

2. Most of the parameters of finishing and finishing-hardening operations directly determine the operational characteristics and reliability indicators of the product under manufacture, because it is there that the final formation of the product quality parameters takes place (parameters of group II, see Figure 3).

3. At the same time, there are such parameters of finishing and finishing-hardening operations, provision of which is effected by the nature of previous operations, which are determined by technological inheritance. Therefore, part of the initial parameters (group III, Figure 3) is functionally related to the parameters of previous intermediate operations.

Finishing and finishing-hardening technological operations carried out by means of surface plastic deformation (SPD) and heat treatment are the "technological barriers" in products production. They minimize the impact of technological inheritability on the formation of the final parameters of the product.

However, most SPD methods do not improve the geometric accuracy of the surface. In the manufacture of products the accuracy achieved in the previous operation usually retains. In addition, the surface can be deformed by 5-10 μm due to the formation of residual compressive stresses in the surface layer during processing of the thin-walled and non-uniformly rigid parts (wall thickness 3-5 mm). Due to the metal plastic flow, when using some methods of surface plastic deformation on the end surfaces of the treated surfaces, uniform inflows of metal with a thickness of 0.03-0.3 mm are formed.

The formation of quality parameters of the product surface layer is a priority task of technological operations implemented by SPD.

Ensuring both dimensional accuracy and surface quality, which is associated with operational characteristics and reliability indicators, requires a detailed dimensional analysis of the process. It is carried out starting with the latest technological operation and ending with blank production.

In this case, the main task of dimensional analysis of the technological process is the choice of a rational blank. The main problems are the choice of optimal criteria for analysing the parameters of the obtained blank and prediction of its state in the technological process operations.

4.2. Analysis of the pressure treatment in blank production

We have only investigated two main processes of blank production: steel pressure treatment and aluminium alloys casting.

Gurson [11], Tvergaard and Needleman [12], Tvergaard and Nielsen [13], McClintock [14], Rice and Tracey [15], Wierzbicki, Bao [16], Xue [17] etc. studied pressure treatment for product manufacturing.

Damage mechanics models are basically classified into two categories: coupled and uncoupled models [18-19].

Coupled models include the effect of damage accumulation in the equation of state [11-13], [17]. For example, continuous damage mechanics (CDM) examines the evolution of damage macroscopically and phenomenologically by introducing an internal variable $D$ to quantify the microscopic material degradation [20].

Unlike coupled, uncoupled models determine the critical state of the load, which is responsible for the occurrence of fracture [14-16]. Loading conditions are usually characterized by a weight function
of equivalent plastic deformation. The corresponding critical equivalent plastic deformation to fracture is expressed as $\varepsilon_f$.

Deformation to fracture strongly depends on the triaxial stress and Lode angle. These models simply provide a double assessment: if a critical load is reached, the fracture occurs; otherwise the structure is safe.

The accumulated damage is not related to the constitutive plasticity model. Therefore, the deterioration of the material properties is not taken into account in the stress-strain curve of the material. Despite these limitations, empirical models are widely used in many applications due to their simple formulation and ease of definition [19].

Lian [19] proposed to differentiate fracture $\varepsilon_f$ and initiation of crack $\varepsilon_i$.

According to this concept, a hybrid approach to modelling plastic damage with three main components derived from the previously considered models is formulated: a model of plasticity to characterize the behaviour (mode) of the material before crack initiation; a phenomenological criterion, which indicates the initiation (formation) of damage; a damage-induced weakened part to characterize the post-damage material behaviour [19].

As soon as $\varepsilon_i$ work in the corresponding stress state, the deformation-induced damage becomes critical up to the final fracture. To represent the damage-induced weakening, a damage evolution law based on the energy dissipated during damaging is introduced. An internal parameter $D$ characterizes the total damage, and a critical value of $D$, $D_{cr}$, represents the final separation of the material environment, that is, fracture [19]:

$$D = \begin{cases} 0, & \varepsilon \leq \varepsilon_i, \\ \frac{\varepsilon - \varepsilon_0}{L} \cdot \frac{2 \cdot G_f}{\varepsilon_i}, & \varepsilon_i < \varepsilon < \varepsilon_f, \\ D_{cr}, & \varepsilon = \varepsilon_f. \end{cases} \quad (1)$$

With this approach to modelling, it is possible to perform a multi-scale characterization of both damage and fracture, and a quantitative representation of the evolution of damage can be obtained to predict the formation of the blank [19].

4.3. Analysis of casting in blank production.

Cast production is a very complex process for theoretical research.

Damageability $D (W)$ in most researches of the causes of material fracture during manufacture is not associated with the structure. Only with the use of energy approaches to describe the processes of damages accumulation, it is considered that as a result of viscoplastic deformation, two types of microdamages develop along the body and along the grain boundaries [1].

The LM-hardness method, developed under the guidance of Academician AA Lebedev, is proposed to control the quality of the specimen structure and materials damage in the studied samples of products. According to the LM-hardness method, derivatives of the physical parameters of absolute values, for example, the scattering of the obtained control results performed by the same devices under the same conditions, serve as an evaluation criterion.

This method is easier to implement, using hardness as a mechanical characteristic, its value being used for indirect evaluation of properties [1], [21].

Homogeneity is a parameter that fully describes the material state when processing the results of hardness control. Homogeneity is described by the Weibull coefficient $m$ and the known Gumbel’s formula [1], [21]:

$$P(\sigma) = 1 - e^{-\left(\frac{\sigma}{\gamma}\right)^m} \quad (2)$$

The Weibull homogeneity coefficient is defined as [1], [21]:

$$m = \frac{\ln(1 - P(\sigma))}{\left(\frac{\sigma}{\gamma}\right)^m}$$
In our research, it is proposed to evaluate the analysis of the material structure for its damageability $D(W)$ using the Weibull coefficient $m$ [1]:

$$D = \frac{m_{\text{max}} - m_i}{m_{\text{max}}}$$  \hspace{1cm} (6)

4.4. Analysis of the basic chart of the formation and transformation of products properties during their manufacture.

The basic chart of the formation and transformation of the products properties during their manufacture for the FOTP planning is presented in Figure 4. The basic chart of the formation and transformation of the products properties during their manufacture for the FOTP planning is presented in Figure 4.

![Figure 4. The Life Cycle Support of Product, analysed from the point of view of technological inheritability mechanics](image)

Optimal operation characteristics and service purpose of the product are established on the basis of the analysis of the product actual operating conditions. Information about the official purpose of the product comes simultaneously to the stages of design and technological preparation of the product.
The manufacture stage for the design of functionally-oriented technological process of the mechanical engineering product production. The technologist, as well as the designer, receives full information on operational characteristics of the product. This allows us to design the process taking into account not only the minimum technological cost of its processing and the maximum load of technological equipment, but also the technological support of the required operational characteristics and reliability indicators.

The design of FOTP of a mechanical engineering product manufacture begins with the formation of the reference data for its implementation. The formation of the reference data for the submicroscopic level of research, in contrast to the macroscopic and microscopic levels of research, has its own specific features. The submicroscopic level of research allows us to investigate thoroughly the technological inheritance of product properties during technological process of its production.

The structure of the technological process is important in the formation of operational characteristics and reliability indicators. Finishing and finishing-hardening operations of the technological process qualitatively provide operational characteristics and reliability indicators, but do not ensure the improvement of dimensional accuracy.

For complex maintenance of the product quality parameters it is necessary to analyse the whole process flow of the product manufacture by means of mechanics of technological inheritability. In this case, considerable attention is paid to blanking as the first link in the technological chain.

At the blanks manufacturing by pressure treatment, it is advisable to use the results of theoretical and rheological researches. Thus technological damageability serves as a criterion of a rational choice of blank parameters. Using the mathematical apparatus of the technological inheritability mechanics, the change of technological damageability for each operation of the technological process of product manufacture is analysed.

When casting a blank, it is advisable to use the method of LM-hardness to determine the Weibull coefficient and technological damage to control the quality of the initial blank. In addition, the choice of a rational route for the product surface treatment is carried out using the method of LM-hardness as well. The obtained results are used to form a rational technological process of the product production.

5. Conclusions
The main conclusions have been drawn basing on the research results.

1. The effective development of mechanical engineering is closely related with research into the Life Cycle Support of Product. Different operating conditions of machine parts lead to the development of different types of degradation of material properties and exhaustion of the service lifetime of the part. The study of the Life Cycle Support of Product allows us to predict the state of the part at a specific moment of a time.

2. Production of blanks is an important step in the Life Cycle Support of Product. It is quite difficult to describe this stage from the point of view of phenomenological theory. We propose to develop a structural model of the formation and transformation of the surface layer properties in terms of the mechanics of technological inheritance, taking into account the stage of blank production.

3. Technological damages in the surface layers of products during blanking operations and after machining should be analysed in terms of the hardness scattering. We propose to use the technological damageability (W), described by means of energy approaches to the processes of damage accumulation, as a criterion for the analysis of the process during blank machining and the entire technological process of the product manufacture.

4. Further research will be conducted on the implementation of the proposed method at other stages of the Life Cycle Support of Product in the mechanical engineering practice.

References
[1] Kusyi Y and Kuk A 2020 Investigation of the technological damageability of castings at the stage of design and technological preparation of the machine Life Cycle, J. Phys.: Conf. Ser. 1426 012034
[2] McDowell D L 2007 Simulation-assisted materials design for the concurrent design of materials and products, *Journal of the Minerals, Metals and Materials Society* 59(9) 21-25

[3] Skoogh A, Perera T and Johansson B 2012 Input data management in simulation-industrial practices and future trends, *Simulation Modelling Practice and Theory* 29 181-192

[4] Denkena B, Mörke T, Krüger M, Schmidt J, Boujnah H, Meyer J, Gottwald P, Spitschan B and Winkens M 2014 Development and first Applications of Gentelligent Components over their Life-Cycle, *CIRP Journal of Manufacturing Science and Technology* 7(2) 139-150

[5] Aftanaziv I, Shevchuk L, Strohan O, Kuk A and Samsin I 2019 Improving reliability of drill pipe by strengthening of thread connections of its elements, *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* 422-29

[6] Stupnytskyy V and Hrytsay I 2020 Computer-Aided Conception for Planning and Researching of the Functional-Oriented Manufacturing Process, *Advanced Manufacturing Processes. InterPartner-2019, Lecture Notes in Mechanical Engineering*, Springer, 309-320

[7] Stupnytskyy V and Hrytsay I 2020 Comprehensive analysis of the product’s operational properties formation considering machining technology, *Archive of mechanical engineering* 67(2) 1-19

[8] Kusyi Y 2019 Technological inheritability of properties for providing of quality parameters of part during it manufacturing, *System Technologies* 5(124) 171-184 (in Ukrainian)

[9] Blumenstein V, Rakhimyanov K, Heifetz M and Kleptzov A 2016 Problem of technological inheritance in machine engineering, *AIP Conference Proceedings* 1698(1) 2-7

[10] Pronikov A 1978 Realibility of machines, Moscow: Mashinostroenie, Russia (in Russian)

[11] Gurson A 1977 Continuum theory of ductile rupture by void nucleation and growth: part I—yield criteria and flow rules for porous ductile media, *Journal of Engineering Materials and Technology–Transactions of the ASME* 99(1) 2-15

[12] Tvergaard V and Needleman A 1984 Analysis of the cup-cone fracture in a round tensile bar, *Acta Metallurgica* 32(1) 157-169

[13] Nielsen K and Tvergaard V 2010 Ductile shear failure or plug failure of spot welds modelled by modified Gurson model, *Engineering Fracture Mechanics* 77(7) 1031-1047

[14] McClintock F 1968 A criterion for ductile fracture by growth of holes, *Journal of Applied Mechanics* 35(2) 363-371

[15] Rice J R and Tracey D M 1969 On ductile enlargement of voids in triaxial stress fields, *Journal of the Mechanics and Physics of Solids* 17(3) 201-217

[16] Bai Y L and Wierzbicki T 2010 Application of extended Mohr-Coulomb criterion to ductile fracture, *International Journal of Fracture* 161(1) 1-20

[17] Xue L 2008 Constitutive modeling of void shearing effect in ductile fracture of porous materials, *Engineering Fracture Mechanics* 75(11) 3343-3366

[18] Besson J 2009 Continuum models of ductile fracture: a review, *International Journal of Damage Mechanics* 19(1) 3-52

[19] Lian J, Sharaf M, Archie F and Muenstermann S 2013 A hybrid approach for modelling of plasticity and failure behaviour of advanced high-strength steel sheet, *International Journal of Damage Mechanics* 22(2) 188-218

[20] Murakami S 2012 *Continuum Damage Mechanics – A Continuum Mechanics Approach to the Analysis of Damage and Fracture*, Springer, Dordrecht, Heidelberg, London, New York

[21] Lebedev A A 2003 A new method of assessment of material degradation during its operating time, *Zalizchnyi Transport Ukrainy* 5 30-33