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Optimization synthesis of technological parameters during manufacturing of the parts

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Highlights

- The developed synthesis method for optimizing the parameters of manufacturing processes made it possible to improve manufacturing efficiency, processing quality, extend the service life of cutting tools, reduce the consumption of energy, and all this created added value for the production process.
- The mathematical model of the technical system is written using the system of Chapman-Kolmogorov differential equations.
- Markov chains were used to study the possible states of objects and to analyse their transition to other states.
- Proposed optimization technique during the manufacturing of parts has been successfully integrated and tested in the real industry.

Abstract

Technological ensuring the reliability of machine parts is realized by failing to reach the limited state of the elements of the technological system: machine – clamping device – metal-cutting tool-part. A method of optimization synthesis of parameters of technological processes of manufacturing machine parts has been developed. Testing the developed methodology, it was found that the metal cutting tool is Meanwhile, research has shown that metal cutting machine has the least influence on the formation of detailed quality-adjustable parameters from all the the weakest element of the technological system in terms of reliability and has the greatest impact on the quality of machined parts. elements of the process media "machine – clamping device – cutting tool". Finally, a concrete example is provided to demonstrate the effectiveness of the proposed method. The proposed technique has been successfully tested for the manufacturing process of the reduction-gear housing.

Keywords

Reliability Engineering, FMEA, FMECA, technological damage, technological graph of reliability, Markov chain.

1. Introduction

Currently, operational safety is the most important characteristic of modern technical systems [19, 3, 48], which involves the analysis of failures and their consequences [21, 4, 30, 20]. The concept of risk is interpreted as a probabilistic criterion for hazards of a particular type, or the number of possible losses (damages) caused by an adverse event, or a combination of these values [4, 29].

At the same time, the development and implementation of the integrated information systems management for technological processes of manufacturing products in the practice of mechanical engineering enterprises is the main mover of economic growth of industrialized countries in the world [18, 23, 32, 55]. These systems give a competitive advantage to manufacturing companies in a global business environment.

The changing priorities of modern mechanical engineering require a thorough study of complex engineering problems and a mathematical apparatus to solve them [14]. In addition, systematic theoretical and experimental investigations are necessary. The appearance of a new fundamental problem – protecting facilities to prevent their failures, accidents, catastrophes – determines new parameters, criteria, risks, and regulatory and technical documents, rethinking the attitude toward providing the products' reliability indicators and operational characteristics [21, 29, 10].

Investigation of the regulated initial quality parameters of machines parts during their manufacturing to provide their operational

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characteristics and indicators of reliability is an essential task for the formation of available products [21, 18, 28, 38]. In order to guarantee the reliability of the final produced products, the cornerstone is the relationship between the reliability of the technological system and the reliability of the manufactured parts.

Technological ensuring the reliability of machine parts is realized by failing to reach the limited state of the elements of the technological system: machine – clamping device – metal cutting tool – part. A method of optimization synthesis of parameters of technological processes of manufacturing machine parts has been developed. To evaluate the presented method, a series of modelling experiments were performed, during which various machining modes were tested and their influence on the cutting edge of the cutting tool during machining of the part was determined. A case study was used to illustrate how to apply the method in real manufacturing conditions. The proposed technique has been successfully tested for the manufacturing process of the gearbox housing.

2. Literature review

A typical approach to international theory and practice on system reliability and risk minimization [15] combines constructive and analytical (quantitative and qualitative) methods [4, 12, 36]. These methods do not replace each other but interact with each other. Potential failures are identified, and measures are taken to eliminate them to reduce their impact or probability of occurrence using the FMEA (Failure Mode and Effects Analysis) and FMECA (Failure Mode Effects and Criticality Analysis) techniques [5, 8, 11]. Reliability parameters are calculated using quantitative methods, methods using the criterion of achieving the product's limit state or its elements [4, 15].

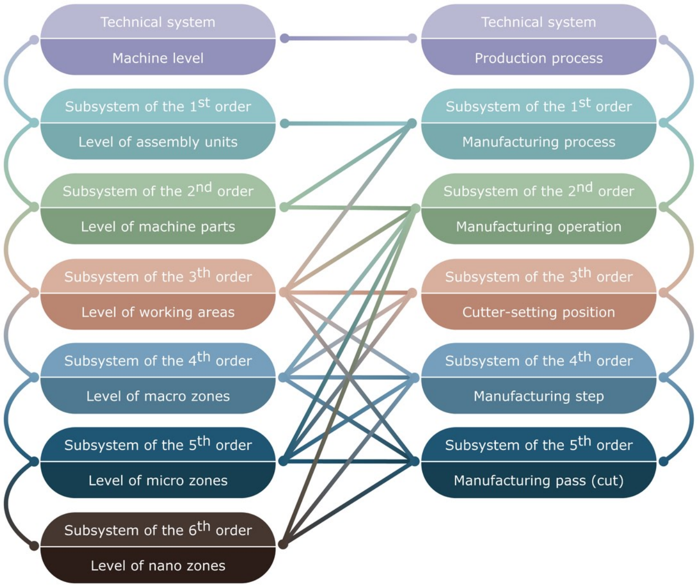

Fig.1. Formation of subsystems of different hierarchical levels according to the theory of technical systems for function-oriented design of technological processes

According to the standard approach to providing the reliability of technical systems [4] to calculate the indicators of reliability and durability, it is necessary to establish the regularities of distribution for the element's failures. The reliability of the technical system is determined based on analysis and study of the established frequencies of distribution for the failures of technical system elements [21, 4]. Mathematical operations for the obtained distribution regularities provide system reliability indicators within the framework of the system (structural, mathematical) theory of reliability [29, 44]. The priority task of the system theory of reliability is the transition from indicators of elements reliability to indicators of system reliability, which complicates the practical solution of modern mechanical engineering problems [56, 43].

The difference in the calculations of the real reliability of the technical system using a system approach consists in the analysis of the reliability of elements and techniques in the general multilevel simulation process using physical and structural models [4, 52]. Physical models of element reliability are used at the lower levels, and structural models – at higher ones [44, 25]. This approach leads to the analysis of reliability indicators in relationship with safety and risk, providing the quality of the technical system. At the same time, ALARA (as low as risk acceptable), currently adopted in most countries, recognizes a particular economic character of providing the reliability and safety of technical systems with minimization of the degree of risk [53, 17].

A hybrid modelling framework for production systems combine machine and system-level models of separate and continuous dynamics to examine the effects of different control variables on production efficiency, reliability, quality, and power consumption [39].

The theory of reliability of technical systems is widely used in the calculations of electrical and electronic circuits. Such circuits have standard components with known reliability characteristics [51, 6].

In the general case, according to the principles of functionally oriented design, a product as part of a technical system is developed as an engineering pyramid from a set of subsystems of different hierarchical levels: the machine level (the final element of satisfying social needs); the level of components that make up the machine - assembly units (subsystem of the 1st order); level of machine parts (subsystem of the 2nd order); the level of the working areas of the part (subsystem of the 3th order); the level of macrozones in the working areas (macroscopic level of research; subsystem of the 4th order); the level of microzones (microscopic level of research; subsystem of the 5th order) and the level of nanozones (submicroscopic/nanoscopic level of research; subsystem of the 6th order) (Fig.1).

Any subsystem is a technical system in relation to a subsystem of the lower level, corresponding to the general principles of systems theory [21, 23].

Analytical or simulation models of algorithms for the functional behaviour of various machines and mechanisms for determining performance or reliability indicators are developed at the stage of their system-engineering design [7, 33, 34]. Complex analytical models are designed (developed) to analyze the functional characteristics and reliability indicators of the research object [41, 47, 50].

The technology of analytical modelling of machines, mechanisms and technological systems makes it possible to use Markov chains to study the possible states of objects and analyse their transition to other states. Such a model of the object of study is represented in the form of a graph of states and transitions, which is actually an intermediary model. The graph of states and transitions is described by the system of Chapman-Kolmogorov differential equations [7, 24, 9, 35].

At the same time, for example, when designing parts and systems of the radio-electronic industry, it is assumed that a specific technical system fails with a certain intensity. The duration of stay in good condition is described by an exponential law with the parameter $\lambda(t)$ = const, where $\lambda(t)$ is the failure rate [6, 7].

The failure rate of basic events in this case:

$$\lambda_i = \frac{1}{T_i} \tag{1}$$

where: T_i is the average value of the duration of the i-th operational block of behavior equivalent to the algorithm.

The technical system is restored after a failure, and the duration of the restoration is distributed according to the Erlang distribution law [6, 7].

The intensity of restoration of the technical system is described by the formula [7]:

$$\mu_{er}(t)=\frac{\alpha\cdot(\alpha\cdot t)^{n-1}}{(n-1)!\cdot\sum_{k=0}^{n-1}\frac{(\alpha\cdot t)^k}{k!}} \tag{2}$$

where: n is the order of the distribution law (shape parameter), α is the scale parameter.

Two events are considered in the general case for a technical system: the "technical system failure" event and the "technical system restoration" event. The graph of states and transitions of the technical system is shown in Fig. 2. The states of such a technical system are characterized by the following probabilities: $P_0(t)$ – the probability that the technical system is ready for work (capable of working) in state S_0; $P_1(t)$ is the probability of the technical system being in a faulty state (being under repair or failure) S_1 [6, 7].

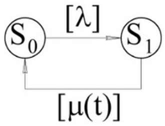

Fig. 2. Graph of states and transitions of a technical system

The mathematical model of such a technical system is presented as a system of differential equations with variable coefficients [7]:

$$\begin{aligned}\frac{dP_0(t)}{dt}&=-\lambda\cdot P_0(t)+\mu_{er}(t)\cdot P_1(t),\\ \frac{dP_1(t)}{dt}&=\lambda\cdot P_0(t)-\mu_{er}(t)\cdot P_1(t).\end{aligned} \tag{3}$$

The state S_1 is replaced by a chain to bring the mathematical model (3) to a homogeneous Markov model, according to the Erlang's method of stages. The number of states in the new chain is determined by the order of the chosen Erlang distribution law. The equivalent graph of states and transitions for the chain ($n = 2$) is shown in Fig. 3 for the transformation of the technical system shown in Fig. 1. On Fig. 3 are denoted by P_{10}, P_{11}, that is, the probability of the technical system staying in fictitious states S_{10} and S_{11}, describing the recovery procedure [5, 6, 43].

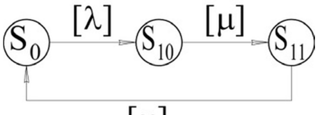

Fig. 3. Graph of states and transitions of a technical system

The mathematical model of a technical system is written using a system of Chapman-Kolmogorov differential equations with constant coefficients after the formation of a graph of states and transitions [7]:

$$\begin{aligned}\frac{dP_0(t)}{dt}&=-\lambda\cdot P_0(t)+\mu\cdot P_1(t),\\ \frac{dP_{10}(t)}{dt}&=\lambda\cdot P_0(t)-\mu\cdot P_{10}(t),\\ \frac{dP_{11}(t)}{dt}&=-\mu\cdot P_0(t)+\mu\cdot P_{11}(t).\end{aligned} \tag{4}$$

The method based on the implementation of the Laplace transformation is used to solve system (4) with a conditionally small number of equations [7]:

$$\begin{aligned}s\cdot p_0(s)-C_0(0)&=-\lambda\cdot p_0(s)+\mu\cdot p_{11}(s),\\ s\cdot p_{10}(s)-C_1(0)&=\lambda\cdot p_0(s)-\mu\cdot p_{10}(s),\\ s\cdot p_{11}(s)-C_2(0)&=\mu\cdot p_{10}(s)-\mu\cdot p_{11}(s).\end{aligned} \tag{5}$$

The values of the constants take the form $C_0(t{=}0){=}1$, $C_1(t{=}0){=}0$ and $C_2(t{=}0){=}0$ for a capable of working technical system at the initial moment of time. In this regard, the solution of the system of linear equations (5) takes the following form:

$$\begin{aligned}p_0(s)&=\frac{(\mu+s)^2}{s^3+(2\cdot\mu+\lambda)\cdot s^2+(\mu+2\cdot\lambda)\cdot\mu\cdot s},\\ p_{10}(s)&=\frac{\lambda\cdot(\mu+s)}{s^3+(2\cdot\mu+\lambda)\cdot s^2+(\mu+2\cdot\lambda)\cdot\mu\cdot s},\\ p_{11}(s)&=\frac{\lambda\cdot\mu}{s^3+(2\cdot\mu+\lambda)\cdot s^2+(\mu+2\cdot\lambda)\cdot\mu\cdot s}.\end{aligned} \tag{6}$$

However, in the analysis of mechanical systems, the indicators of reliability and durability change due to a large number of possible design options and manufacturing technology, different operating conditions of a particular element in various machines and mechanisms. This complicates their prediction of operating conditions [25].

According to the principle of resource-dependent behaviour, elements of a real mechanical system are interdependent. Their failures or limit states are related to each other and are determined by the influence of common factors [15]. Modern approaches to the calculation of technical system reliability indicators are based on applying the concept of the limit state of the system element [4, 25]. A review of the literature has shown that due to the lack of maintenance of the functional characteristics of production systems, the reliability of the technological system is problematic to evaluate exactly. For this purpose, a method of optimization synthesis of parameters of technological processes was developed to fully describe the state of the technological system, taking in to account the machining modes, physical-mechanical characteristics of the processed material, and the desired machining accuracy and surface quality of the part.

3. Research methodology

The output parameters are formed as a result of sequential processing of the workpiece, which is analysed by the technological inheritability of the part properties. As a rule, regulated indicators are set for each operation. Each operation, as a rule, has its own regulated indicators. They are provided due to technological transitions in the processing of parts [23, 37].

The probability of failure to reach the limit state of the workpiece part $P_{Xij}(r,k,\ldots.t)$ for the j-th parameter in the i-th technological operation of the technological process of manufacturing, taking into account the theorem of adding incompatible events, is determined by the formula:

$$P_{X_{ij}}\left(r,k,.....t\right)=\prod_{j=1}^{q_V}\left(1-F_{X_{ij}}\left(r,g,.....t\right)\right) \tag{7}$$

where: X_{ij} ($j\in[1;q_i]$) is defined the j-th output parameter X for the i-th technological operation; F_{Xij} ($r,k,....t$) is the formation of the limit state of the workpiece by the j-th parameter in the i-th technological operation of the technological process during production.

Output parameters after the last technological operation: $X_{nj}=X_j(j\in[1;m])$, where: m – the total number of output parameters. The output parameters q_i for the *i-th* technological operation form a set of input parameters for (i+1) operation. However, only some of them will be included in the set of output parameters of the final product according to the synergistic approach: $q_{0i}<q_i$ [13].

The output parameters of mechanical engineering parts are classified into three groups [21].

The output parameters of group I for mechanical engineering parts include a few of the output parameters of intermediate operations (for example, physical-mechanical characteristics of parts material). The finishing and strengthening operations of parts manufacturing provide a lot of output parameters according to accuracy, quality of surfaces, operational characteristics and reliability indicators of mechanical engineering objects (the output parameters of group II for mechanical engineering parts). The output parameters of group III for mechanical engineering objects are functionally related to previous intermediate operations parameters according to technological inheritability and technological inheritance during parts manufacturing [22].

Then the total number of output parameters is:

$$m=q_n+\sum_{i=0}^{n-1}q_{oi} \tag{8}$$

where: q_n is the number of output parameters obtained in the last operation and functionally related with the technological inheritability and technological inheritance during parts manufacturing (the output parameters of group II and III); q_{oi} is the number of output parameters for the i-th technological operation which form the output parameters of group I.

The probability of the working state of the part $P(t)$ in the general case for the technological process, independently forming each initial parameter, is determined as follows:

$$P\left(r,k,.....t\right)=\prod_{i=1}^{n}P_i\left(t\right)=\prod_{i=0}^{n}\prod_{j=1}^{m}P_{X_{ij}}\left(r,g,.....t\right) \tag{9}$$

where: P_{Xij} ($r, g,....t$) is the probability of failure to reach the limit state of the part by the j-th parameter in i-th technological operation of the technological process of its manufacture.

Analysis of the probability of providing regulated quality parameters of the workpiece is appropriate, taking in to account the influence of elements of the technological system in the i-th technological operation, using the mathematical apparatus for implementation of Markov processes [26, 27]. The technological graph of reliability for the i-th technological operation, described by Markov chains, is shown in Fig. 4.

Vertices of the technological graph of reliability in the i-th technological operation (Fig. 4) describe the possibility of the technical system in ($k+3$) possible states taking into account the influence of the technological environment elements: 1 are aspects of the metal-working technological system: metal-cutting machine (MCM), clamping device located on the metal-cutting machine (MCMD), metal cutting tool (MCT) during the processing of the workpiece in the i-th technological operation is not in the limit state that provides the formation of regulated quality parameters of the part according to with the requirements of design and technological documentation; 2, 3, 4,…, (k+3) are metal-cutting machine, clamping device on the metal-cutting machine, the first / k-th metal-cutting tool in general or their elements, in particular, are in the limit state in the metal-working technological system during processing of the workpiece in the i-th technological operation, respectively. In Fig. 2 λ_{MCM_i}, λ_{CD_i}, $\lambda_{MCT\_i\_1}$, …., $\lambda_{MCT\_i\_(k)}$ are failure rates of the metal-cutting machine, the clamping device on the metal-cutting machine and the first / k-th metal-cutting tool or their elements in the i-th technological operation during workpiece processing.

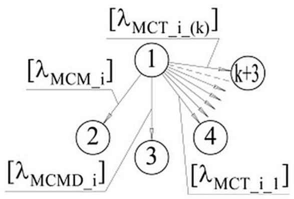

Fig. 4 Technological graph of the reliability for the i-th technological operation that is described by Markov chains to predict the probability of providing regulated quality parameters of the workpiece, taking in to account the influence of the technological system elements

According to Fig. 4, notation of probabilities of events is introduced: $P_1(t)$ is the probability of the technical system in state 1 that characterizes the ensuring of regulated parameters of the workpiece during its processing in the i-th technological operation in case of not reaching the limit states of the metal-cutting machine, clamping device and tool (or tools) in general and their elements in particular; $P_2(t)$, $P_3(t)$, $P_4(t)$, …., $P_{(k+3)}(t)$ is the probability of the technical system in states 2, 3, 4, ….., (k+3), characterizes the failure to provide the regulated parameters of the workpiece during its processing in the i-th technological operation, provided that the metal-cutting machine reaches the limit state, a clamping device, the first / k-th metal-cutting tool in general and (or) their elements in particular, respectively.

The system of Chapman-Kolmogorov differential equations for the technological graph of reliability (Fig. 4), taking in to account the influence of elements of the metal-working technological system on providing the regulated quality parameters of machine product for the i-th technological operation, looks like:

$$\begin{aligned}
&\frac{dP_1(t)}{dt}=-\lambda_{MCM\_V}\cdot P_1(t)-\lambda_{MCMD\_V}\cdot P_1(t)-\\
&\sum_{k=1}^{z}\lambda_{MCT\_(k)i}\cdot P_1(t),\\
&\frac{dP_2(t)}{dt}=\lambda_{MCM\_V}\cdot P_1(t),\\
&\frac{dP_3(t)}{dt}=\lambda_{MCMD\_V}\cdot P_1(t),\\
&\frac{dP_4(t)}{dt}=\lambda_{MCT\_i\_1}\cdot P_1(t),\\
&\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\\
&\frac{dP_{z+3}(t)}{dt}=\lambda_{MCT\_i\_z}\cdot P_1(t),\\
&P_1(t)+P_2(t)+P_3(t)+P_4(t)+\ldots\ldots\ldots P_{z+3}(t)=1,\\
&\mathrm{t}\in[0;\mathrm{t}],
\end{aligned} \tag{10}$$

where: k is the k-th metal-cutting tool in the i-th technological operation (i = 1,… z).

The last equation in the system (10) represents the addition theorem of incompatible events. This equation is presented in the form from the viewpoint of the physical essence of prediction of the regulated workpiece parameters during its processing in the i-th technological operation, taking in to account the influence of elements of the metalworking technological system:

$$P_{W(\mathrm{P})\,\mathrm{i}}\left(r,g,....t\right)+F_{MCM\,\mathrm{i}}\left(r,g,....t\right)+ \\ +F_{MCMD\,\mathrm{i}}\left(r,g,....t\right)+\sum_{k=1}^{z}F_{MCT\,(\mathrm{k})\,\mathrm{i}}\left(r,g,....t\right)=1 \tag{11}$$

where: $P_{W(P)i}$ $(r, g, ...t)$ is the probability of providing regulated quality parameters of the workpiece in the i-th technological operation of the technological process of the product manufacturing in case of failure to reach the limit state of the metal-cutting machine, clamping device located on the metal-cutting machine and metal-cutting tool (or tools) in general and their elements in particular; F_{MCMi} $(r, g, ...t)$ is the probability of failure to provide regulated quality parameters in the i-th technological operation of the technological process of product manufacturing, when the limit state is reached by the metal-cutting machine in general or its elements in particular; F_{MCMDi} $(r, g, ...t)$ is the probability of failure to provide the regulated quality parameters in the i-th technological operation of the technological process of product manufacturing, when the limit state is reached by the clamping device on a metal-cutting machine in general or its elements in particular; $F_{MCT\,i}$ $(r, g, ...t)$ is the probability of failure to provide regulated quality parameters in the i-th technological operation of the technological process of product manufacturing when the limit state is reached by the metal-cutting tool (or tools) in general or its (their) elements in particular; k is the k-th metal cutting tool in the i-the technological operation, $[k\in 1;z]$.

The probability of providing the regulated quality parameters of the workpiece in the i-th technological operation of the technological process of product manufacturing in case of not reaching the limit state of the metal-cutting machine, clamping device on the metal-cutting machine and metal-cutting tool (or tools) in general and their elements in particular, is determined by (12):

$$P_{W(P)\,\mathrm{i}}\left(r,g,....t\right)=1-F_{MCM\,\mathrm{i}}\left(r,g,....t\right)- \\ F_{MCMD\mathrm{i}}\left(r,g,....t\right)-\sum_{k=1}^{z}F_{MCT\,(\mathrm{k})\mathrm{i}}\left(r,g,....t\right) \tag{12}$$

The probability of providing the regulated quality parameters of the workpiece in the i-th technological operation of the technological process of manufacturing the product is determined by the possibilities of reaching the limit state by the metal-cutting machine F_{MCMi} $(r, g, ...t)$, the clamping device on metal-cutting machine F_{MCMDi} $(r, g, ...t)$ and metal-cutting tool (or tools) F_{MCTi} $(r, g, ...t)$ in general and their elements in particular.

In addition, the elements of the metal-working technological system have specific reliability parameters according to the technical requirements for their manufacturing and operation that provide regulated quality parameters of machine parts during their formation, control and assembly.

In this case, the conditions for providing serviceability to technological problems are determined by:

$$\begin{aligned} &P_{W(P)\,\mathrm{i}}\left(r,g,....t\right)\geq\left[P_{W(P)}\right]; \\ &P_{\mathrm{MCM\,i}}\left(r,g,....t\right)\geq\left[PMCM\right]; \\ &P_{MCMD\,\mathrm{i}}\left(r,g,....t\right)\geq\left[P_{MCMD}\right]; \\ &P_{MCT(\mathrm{k})\,\mathrm{i}}\left(r,g,....t\right)\geq\left[PMCT\right], \end{aligned} \tag{13}$$

where: $P_{W(P)i}$ $(r, g, ...t)$, P_{MCMi} $(r, g, ...t)$, P_{MCMDi} $(r, g, ...t)$, $P_{MCT(k)i}$ $(r, g, ...t)$ are the probability of providing the regulated quality parameters in the i-th technological operation of technological process of the manufacturing, when the limit state is not reached by the metal-cutting machine, a clamping device on the metal-cutting machine and k-th metal-cutting tool, respectively, in general or its (their) elements in particular; $[P_{W(P)}]$, $[P_{MCM}]$, $[P_{MCMD}]$, $[P_{MCT}]$ is regulated probability of providing a certain indicator of reliability for the part, metal-cutting machine, clamping device and metal-cutting tool.

In this case, the number of technological steps within the content and the number of technological operations within the technological process of the part manufacturing is optimized; that is, the number of subsystems at different levels of the technical system is optimized. This allows us in the self-organized systems to control their adaptability and reliability of the conditions of formation and fluctuations by changing the number of subsystems [13, 54]. Entropy increases in closed independent subsystems [21, 13]. To provide this condition, the distribution of probabilities and the introduction of isolated reserves are used in disconnected open subsystems that exchange resources and information with the external environment.

4. The study of the failure rate for the elements of the technological system "machine – clamping device - tool – part"

4.1. General provisions

The failure rate is a priority indicator of the reliability of non-repaired and non-restorated facilities. The failure rate is the relative density of the probability of an object failure, which is determined under the condition that a failure does not occur by the considered point in time [16]. In the general case [42]:

$$\lambda\left(t\right)=\frac{f\left(t\right)}{P\left(t\right)}, \tag{14}$$

where: $f(t)$ is the distribution density of uptime, $P(t)$ is the probability of non-failure operation of an object of a technical system, subsystem, etc.

4.2. Determination of the failure rate for the main technological equipment (metal-cutting machines) in the system "machine – clamping device - tool - part" in the manufacture of parts

The operation of metal-cutting equipment implies that the system of maintenance and repair of the machine is implemented clearly in accordance with its repair cycle. This minimizes the impact of wear of components and parts of metal-cutting machines. In this regard, the exponential distribution law of the parameters of metal-cutting machines is used to conduct research in the process of machining parts, including reduction-gear housing as example.

The restoration of the technical parameters of the main technological equipment lost during operation is carried out in accordance with its repair cycle. The duration of the repair cycle directly depends on the degree of accuracy of the machine, its operating conditions, cutting modes during the machining of parts, the type of production and the service life of rapidly wearing machine parts.

According to the production experience of the Lviv plant of milling machines, the average duration of the repair cycle is 30,000 working hours. At the same time, the repair cycle is about 90 months, the overhaul period is 9 months, and the period between inspections is 5 months for the work in two shifts.

The metal-cutting machine is the strongest element in the process media "machine – clamping device – tool". Since the overhaul period is set in the repair cycle of a metal-cutting machine in accordance with the need to restore its technical characteristics lost during operation, the failure rate of metal-cutting machine with an exponential law of reliability can be defined as follows:

$$\lambda_{MCM} = \frac{1}{T_{IT\_MCM}}, \tag{15}$$

where: T_{IT_MCM} is the average overhaul period in the repair cycle of metal-cutting machine, min.

$$T_{IT\_MCM} = \frac{F_{r.} \cdot \left[T_{IT\_MCM} \right]}{12} \cdot 60, \tag{16}$$

where: $[T_{IT\_MCM}]$ – the average overhaul period in the repair cycle of metal-cutting equipment in months, $F_{r.}$ – the actual annual fund of the equipment operation time in hours; for two-shift operation $F_{r.}$=4055 h [21, 46]. From production experience, we take $[T_{IT\_MCM}]$ = 9 months. Then:

$$T_{IT\_MCM} = \frac{4055 \cdot 9}{12} \cdot 60 = 182475 \text{ min.}$$

Based on production experience, the average overhaul period in the repair cycle of metal-cutting equipment is assumed to be the same for universal metal-cutting machines, i.e. T_{IT_MCM}=182475 min.

$$\lambda_{MCM} = \frac{1}{182475} = 5.48 \cdot 10^{-6} \text{ 1/min.}$$

Hence λ_{MCM}=5.48·10^{-6} 1/min.

4.3. Calculation of the failure rate of clamping device in the system “machine – clamping device - tool - part” in the manufacture of parts

As stated earlier, during the operation of metal-cutting equipment, we accept that the system of maintenance and repair of technological equipment is implemented clearly in accordance with its repair cycle. The failure rate of clamping device is determined by the exponential law of reliability according to the formula [21]:

$$\lambda_{MCMD} = \frac{1}{T_{MCMD}}, \tag{17}$$

where: T_{MCMD} – established trouble-free time between failures of the clamping device.

Based on production experience for mechanized clamping devices on universal machines, it can be stated that T_{MCMD} =1500 h.

Then:

$$\lambda_{MCMD} = \frac{1}{1500 \cdot 60} = 1.111 \cdot 10^{-5} \text{ 1/min.}$$

Consequently, the failure rate of clamping devices on universal metal-cutting machines λ_{MCMD}= 1.111·10^{-5} 1/min.

4.4. Determination of the failure rate of a metal-cutting tool in the system “machine – clamping device - tool - part” in the manufacture of parts

The metal-cutting tool is the weakest element of the process media “machine – clamping device - tool” in terms of reliability [40]. The exponential distribution is used among the distribution laws of random variables to assess the reliability parameters of a metal-cutting tool, which is justified by the following criteria [21, 40]:

1) The probability of failure-free operation is always underestimated with an exponential distribution in comparison with other statistical laws, which determines more stringent requirements for the reliability parameters of a metal-cutting tool;
2) The actual duration of the metal-cutting tool is much less than its stability when analyzing reliability indicators for a certain manufacturing step (operation) when processing with this tool. This makes it possible not to take in to account its wear, and the failure rate over a short period of time can be assumed to be a constant value.

The rejection of the worst-quality samples of metal-cutting tools occurs during their operation during the machining of workpieces. Therefore, the failure rate remains practically unchanged for a batch of metal-cutting tools [2].

The failure rate is assumed to be equal to the destruction rate of the metal-cutting tool λ_{MCT_0} in the calculations of the reliability indicators of the elements of the technological system “machine – clamping device – tool – part” for the exponential distribution [40]:

$$\lambda_{MCT} = \lambda_{MCT\_0} = \lambda_{MCT\_bas.} \cdot k_{f.}, \tag{18}$$

where: $\lambda_{MCT\_bas.}$ – basic failure rate of the tool according to exponential reliability law, 1/min, $k_{f.}$ – dimensionless correction factor that takes in to account the proportion of sudden failures for a given type of tool.

The basic failure rate of the tool is determined by the formula [40]:

$$\lambda_{MCT\_bas.} = \frac{1}{T}, \tag{19}$$

where: T – cutting tool life, min.

After substituting (19) into (18), we get:

$$\lambda_{MCT} = \lambda_{MCT\_0} = \frac{k_{f.}}{T}. \tag{20}$$

Based on the recommended values of durability and production experience, the failure rate λ_{MCT} is calculated for metal-cutting tools that are used for processing the gearbox housing, in particular [21]: for face mills – 2.5·10^{-3}-3·10^{-3}; for lathe tools – 2.7·10^{-2}; for drills – 2.22·10^{-2}-6.67·10^{-2}; for core drills and countersinks – 3.33·10^{-2}; for reamers – 2.22·10^{-2}-3.33·10^{-2}; for taps – 1.11·10^{-2}.

5. Mathematical modeling of technological support of quality parameters in the manufacture of parts during their machining operations

Optimization synthesis involves the following problems [21, 49, 1]: substantiation of specific indicators of reliability of machine parts relative to the regulated indicators of machine reliability; establishment of the limit value of the machining time at a particular technological step (technological operation) of mechanical processing of the part according to specific reliability indicators; determination of optimal modes of part processing according to the limit value of the machining time by the calculated reliability indicators.

If condition (13) is not met, the parameters of the technological operation, in particular the elements of the cutting modes that determine the central machining time or (and) the resistance of the tool at the limiting technological step, are optimized.

Determination of the regulated reliability indicators of products concerning the regulated indicators of reliability of the machine is not the problem of this paper. The value of the gamma-percentile operating time to failure $P(t_\gamma)$ = 1.0; 0.99; 0.95; 0.90; 0.80; 0.50 is regulated by standards depending on the responsibility of the element and its cost [48].

The provision of technological reliability parameters, taking in to account the influence of a specialised system of metal-processing, is analysed in technological operations and steps during the manufacture of mechanical engineering part–a reduction-gear housing (enterprise “Agromashproekt”, Lviv, Ukraine).

Casting of the cast iron 30B (USA Standard ASTM A 48) is used for a workpiece of the reduction-gear housing. This workpiece’s technological route of machining consists of 10 technological machining operations. Metal-cutting and measuring tools, and technological equipment correspond to this type of production.

Technological operation 005 (horizontal milling) will be analysed in detail (Fig. 5, Table 1).

The reduction-gear housing represents one of the most difficult-to-cut classes of the mechanical engineering parts – “Cases”. It serves as a datum’s part for the location of shafts with gears, bearings, and other gearbox elements.

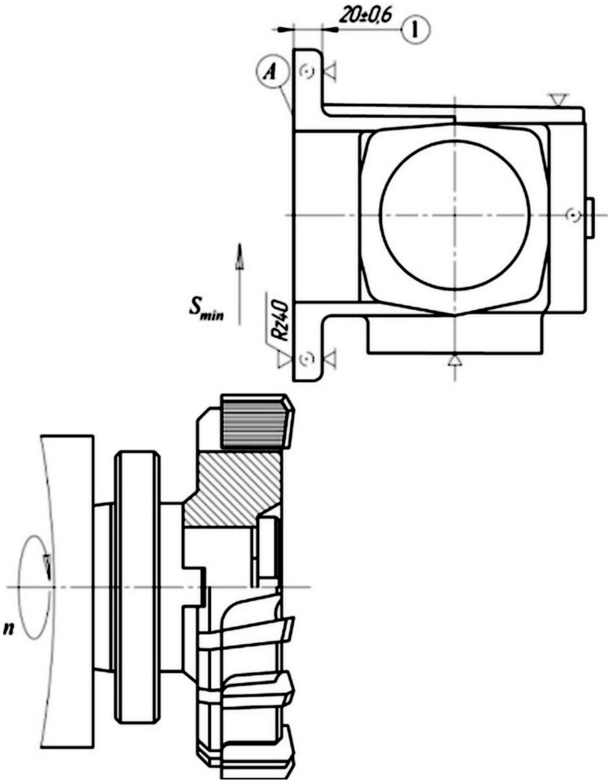

Fig. 5. Sketch map of the operation 005 (horizontal-milling) for machining of reduction-gear housing

A system of the Chapman-Kolmogorov differential equations was developed for operation 005 of the technological process of manufacturing the reduction-gear housing for the technological graph of reliability (Fig. 6):

$$\begin{aligned}
&\frac{dP_1(t)}{dt} = -\lambda_{MCM\_005}\cdot P_1(t) - \lambda_{\square CMD\_005}\cdot P_1(t) \\
&-\lambda_{\square CT\_005}\cdot P_1(t), \\
&\frac{dP_2(t)}{dt} = \lambda_{MCM\_005}\cdot P_1(t), \\
&\frac{dP_3(t)}{dt} = \lambda_{MCMD\_005}\cdot P_1(t), \\
&\frac{dP_4(t)}{dt} = \lambda_{MCT\_005}\cdot P_1(t), \\
&P_1(t)+P_2(t)+P_3(t)+P_4(t)=1, \\
&\ t\in[0;t].
\end{aligned} \tag{21}$$

The partial solution of the system of differential equations (21), which is necessary for the optimization synthesis, as:

$$P_1(t) = e^{-\left(\lambda_{MCM\_005}+\lambda_{MCMD\_005}+\lambda_{MCT\_005}\right)\cdot t} + C_1. \tag{22}$$

If P_1 (t = 0) = 1, C_1 (t = 0) = 0.

At that time $P_1(t)$ as element of equation (12) is equal:

$$P_1(t) = e^{-\left(\lambda_{MCM\_005}+\lambda_{MCMD\_005}+\lambda_{MCT\_005}\right)\cdot t} \tag{23}$$

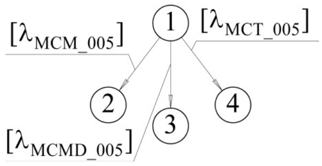

Fig. 6. Technological graph of reliability for operation 005 for machining of reduction-gear housing

After the substitution λ_{MCM_005}=5.48·10^{-6} min^{-1}; λ_{MCMD_005}=1.111·10^{-5} min^{-1}; λ_{MCT_005}=2.5·10^{-3} min^{-1} (see 4.2-4.4) in expression (22), is obtained $P_1(t)=e^{-2.517\cdot 10^{-3}\cdot t}$.

$P_2(t)$, $P_3(t)$, $P_4(t)$ are calculated after solving the system of differential equations (21):

$$P_2(t) = \frac{\lambda_{MCM\_005}\cdot e^{-\left(\lambda_{MCM\_005}+\lambda_{MCMD\_005}+\lambda_{MCT\_005}\right)\cdot t}}{-\left(\lambda_{MCM\_005}+\lambda_{MCMD\_005}+\lambda_{MCT\_005}\right)} + \\ +\lambda_{MCM\_005}\cdot C_1\cdot t + C_2;$$

$$P_3(t) = \frac{\lambda_{MCMD\_005}\cdot e^{-\left(\lambda_{MCM\_005}+\lambda_{MCMD\_005}+\lambda_{MCT\_005}\right)\cdot t}}{-\left(\lambda_{MCM\_005}+\lambda_{MCMD\_005}+\lambda_{MCT\_005}\right)} + \\ +\lambda_{MCMD\_005}\cdot C_1\cdot t + C_3;$$

Table 1. Technological operation of machining a workpiece “Reduction-gear housing”

Number of the operation	The name of the operation and the description of steps	Elements of the metal-treatment technological systems			Machining time, min	
		MCM	MCT	MCMD	in steps	in operation
005	Horizontal-milling. To mill a reference plane A, providing the specified dimension 1 (Fig. 2)	Universal milling machine	Face milling cutter	Clamping device	1.48	1.48

$$P_4(t)=\frac{\lambda_{MCT\_005}\cdot e^{-\left(\lambda_{MCM\_005}+\lambda_{MCMD\_005}+\lambda_{MCT\_005}\right)\cdot t}}{-\left(\lambda_{MCM\_005}+\lambda_{MCMD\_005}+\lambda_{MCT\_005}\right)}+$$
$$+\lambda_{MCT\_005}\cdot C_1\cdot t+C_4.$$

After substituting C_1 (t = 0) = 0, formulas in symbolic form can be written as follows:

$$C_2=\frac{\lambda_{MCM\_005}}{\left(\lambda_{MCM\_005}+\lambda_{MCMB\_005}+\lambda_{MCT\_005}\right)};$$
$$C_3=\frac{\lambda_{MCMD\_005}\cdot 1}{\left(\lambda_{MCM\_005}+\lambda_{MCM\square\_005}+\lambda_{MCT\_005}\right)};$$
$$C_4=\frac{\lambda_{MCT\_005}}{\left(\lambda_{MCM\_005}+\lambda_{MCM\square\_005}+\lambda_{MCT\_005}\right)}.$$

Quantitative values of constants: $C_2=2.178\cdot 10^{-3}$; $C_3=4.415\cdot 10^{-3}$; $C_4=0{,}993$.

The components of equation (12) are presented as:

$$F_2(t)=\frac{\lambda_{MCM\_005}\cdot e^{-\left(\lambda_{MCM\_005}+\lambda_{MCMD\_005}+\lambda_{MCT\_005}\right)\cdot t}}{-\left(\lambda_{MCM\_005}+\lambda_{MCMD\_005}+\lambda_{MCT\_005}\right)}+2.178\cdot 10^{-3};$$

$$F_3(t)=\frac{\lambda_{MCMD\_005}\cdot e^{-\left(\lambda_{MCM\_005}+\lambda_{MCMD\_005}+\lambda_{MCT\_005}\right)\cdot t}}{-\left(\lambda_{MCM\_005}+\lambda_{MCMD\_005}+\lambda_{MCT\_005}\right)}+4.415\cdot 10^{-3}; \tag{24}$$

$$F_4(t)=\frac{\lambda_{MCT\_005}\cdot e^{-\left(\lambda_{MCM\_005}+\lambda_{MCMD\_005}+\lambda_{MCT\_005}\right)\cdot t}}{-\left(\lambda_{MCM\_005}+\lambda_{MCMD\_005}+\lambda_{MCT\_005}\right)}+0.993.$$

The probabilities of ensuring the regulated parameters of the product workpiece are calculated in the process of its manufacturing by steps (subsystems of the 2nd order) and by technological operations (subsystems of the 1st order) if the limit states of the elements of the technological environment are not reached during the development of the technological process (technical system) for the manufacture of the reduction-gear housing when solving a system of differential equations. The calculated probabilities are grouped by surface treatment methods within a certain operation. After that, the probabilities of ensuring the regulated parameters of the workpiece of the part are determined if the limiting states of the elements of the process media "metal-cutting machine – clamping device – tool" are not reached in total for the surface (set of surfaces). Chamfering for internal and external cylindrical surfaces, threaded elements, etc. is interpreted under the totality of surfaces. Determining the probabilities of ensuring regulated quality parameters in the process of machining parts have their own characteristics for the principles of object-oriented and functionally-oriented design. The probability of ensuring the regulated parameters of product quality when the limit states of the elements of the process media "metal-cutting machine – clamping device – tool" for a certain technological operation is not reached is calculated as the probability of a sequence of independent events when multiplying the probabilities by manufacturing steps for the principle object-oriented design of technological processes for the manufacture of parts. In contrast, the probability of ensuring the regulated quality parameters of the product when the limiting states of the elements of the process media "metal-cutting machine – clamping device – tool" for a certain technological operation is not reached is defined as the probability of ensuring the quality parameters of the datum surface with high requirements for accuracy and quality of its processing within the technological operation for the principle of functionally oriented design of technological processes for manufacturing parts. The probability of ensuring the regulated parameters of product quality for a technological operation is defined as the probability of a sequence of independent events for one surface (set of surfaces) when processing surfaces of the same type with the same technological routes. The value of the probability of ensuring the regulated parameters of product quality in total for technological operations according to the principles of object-oriented and function-oriented design of technological processes for manufacturing parts will be the same for an operation with one manufacturing step.

The results of computer simulation for operation 005 of processing the reduction-gear housing are presented in Fig. 7 and Fig. 8.

Numerical values of probabilities: $P_1(t)=0.996$; $F_2(t)=8.09\cdot 10^{-6}$; $F_3(t)=1{,}64\cdot 10^{-5}$; $F_4(t)=3.69\cdot 10^{-3}$ calculated after substituting the values $\lambda_{MCM\_005}=5.48\cdot 10^{-6}$ min^{-1}; $\lambda_{MCMD\_005}=1.111\cdot 10^{-5}$ min^{-1}; $\lambda_{MCT\_005}=2.5\cdot 10^{-3}$ min^{-1} (see 4.2-4.4), $t_0=1.48$ min for machining the reduction-gear housing at operation 005.

The probability of ensuring the regulated parameters of the product workpiece during its processing at operation 005 of the reduction-gear housing when the limit states of the elements of the process media "metal-cutting machine – clamping device – tool" are not reached is shown in Fig. 7. The limiting values of the direct manufacturing time of the workpiece at operation 005 are calculated for the regulated value of the gamma-percentile operation time to failure.

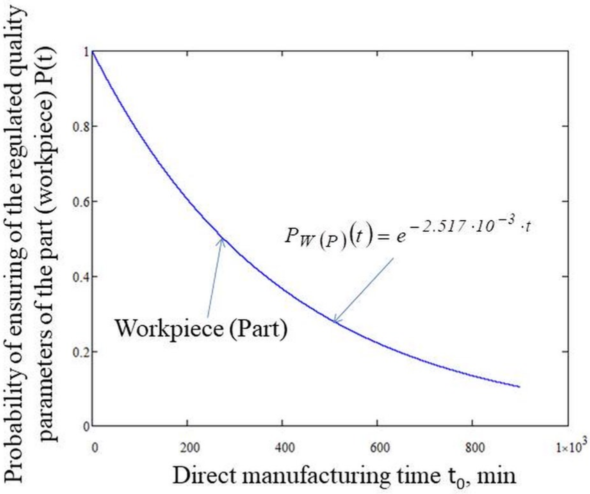

Fig.7. The probability of ensuring the regulated parameters of the workpiece of the reduction-gear housing during its processing at operation 005 if the limit states of the elements of the process media are not reached

When testing the developed methodology, it was found that the metal-cutting tool is the weakest element in the technological system in terms of reliability and has the greatest impact on the quality of parts. At the same time, the durability of a metal-cutting tool serves as its average time to failure. The metal-cutting machine has the least influence on the formation of regulated parameters for the quality of parts from the elements of the process media "machine – clamping device – tool".

6. Optimization synthesis of the technological process of manufacturing the reduction-gear housing

The limit value of the machining time of the technological transition (operations, etc.) is determined during the design and technological preparation of production in according with the established regulated reliability parameters and the law of their distribution.

The machining time maximum in a specific technological operation is the objective function of the problem of optimization and the process of the synthesized parameters:

$$t_{0\max}\left(t,S,n\left(V\right)\right)\rightarrow \max, \tag{25}$$

where: t, S, n, V are elements of the cutting modes: the cutting depth, the feed rate, the spindle rotation speed, and the cutting speed, respectively.

The system of equations for the problem optimization in the general case for regulated gamma-percentile operating time to failure is written as:

$$\begin{gathered}(t)=e^{-(A\cdot t)};\\ \begin{cases}P(t)=P\left(t_{\gamma 1}\right);P(t)=P\left(t_{\gamma 2}\right);P(t)=P\left(t_{\gamma 3}\right);\\ P(t)=P\left(t_{\gamma 4}\right);P(t)=P\left(t_{\gamma 5}\right);P(t)=P\left(t_{\gamma 6}\right);\end{cases}\end{gathered} \tag{26}$$

where: $P(t)=e^{-(A\cdot t)}$ is a reliability function obtained as a result of the solution of the system of the Chapman-Kolmogorov differential equations for a particular technological operation; $P\left(t_{\gamma 1}\right)$, …, $P\left(t_{\gamma 6}\right)$ are regulated gamma-percentile operating times to failure.

The solution to the optimization problem for planning the technological process of parts manufacturing is of the form:

$$t_{0k}\leq\left[t_0\right], \tag{27}$$

where: t_{0k} is the machining time for implementing the k-th technological step (k = 1,…. n), $[t_0]$ is the limit value of the machining time according to the regulated reliability indicator regularity of its change for a particular workpiece.

The machining time for machining operations:

- for feed per spindle revolution of the metal-cutting tool (workpiece of a part):

$$t_0=L_{mach.st.}\Big/\left(S_{0\,pasp.}\cdot n_{pasp.}\right), \tag{28}$$

- for feed per minute of the metal-cutting tool (workpiece of a part):

$$t_0=L_{mach.st.}\big/S_{\min.pasp.}\,, \tag{29}$$

where: $L_{mach.st.}$ is the calculated full required length of the machining step of the metal-cutting tool, $S_{0pasp.}$, $S_{min.pasp.}$, $n_{pasp.}$ are values of feed per spindle revolution, feed per minute and rotary speed according to the certified data of the metal-cutting machine, respectively.

$$L_{mach.st.}=\ell+\ell_1+\ell_2\,, \tag{30}$$

where: ℓ is the length of the surface to be machined, mm, ℓ_1 is the length of travel required for cutting tool approach, mm, ℓ_2 is the length of overtravel of the cutting tool, mm.

The calculated length of the machining step of the metal-cutting tool remains constant while processing a specific surface of the workpiece at the technological step of a particular technological operation.

The following conditions will be the optimization criteria for a constant value of the working stroke of the metal-cutting tool ($L_{mach.st.}$ = const.):

$$\begin{gathered}S_0\geq\left[S_0\right],\\ n\geq\left[n\right],\\ S_{\min.}\geq\left[S_{\min.}\right],\\ T_{MCT}\leq\left[T_{MCT}\right],\end{gathered} \tag{31}$$

where: $[S_0]$, $[n]$, $[S_{min}]$ are the limit values of feed per spindle revolution, rotary speed and feed per minute for a particular method of processing and providing the required accuracy, quality of the surface layer of the workpiece and reliability indicators; T_{MCT}, $[T_{MCT}]$ are the actual and limit value of the tool resistance, respectively.

The results of solving the optimization problem (27) for a specified gamma-percentile operating time to failure (t_γ) in the manufacture of the reduction-gear housing in operation 005 is shown in Fig. 9. The gamma-percentile time to failure for a specific part is determined on the basis of the calculation of dimensional chains based on the gamma-percentile operating time to failure of the machine regulated by the official purpose.

This article considers a variant of a complex solution to the problem for all possible regulated values of the gamma-percentile time to failure (Fig. 9). The dependence graph of the probability of providing regulated parameters in the process of machining the workpiece of the reduction-gear housing at operation 005 $P_1(t)=e^{-2.517\cdot 10^{-3}\cdot t}$ is drawn for the results of mathematical modelling. The regulated parameters of the gamma-percentile time to failure (1.00; 0.99; 0.95; 0.90; 0.80; 0.50) are plotted along the y-axis. After that, lines parallel to the x-axis are built until they intersect with the resulting graph. The intersection points will give the desired values of the limiting values of the direct manufacturing time for the regulated parameters of the gamma-percentage time to failure in operation 005.

The system of equations (26) for operation 005 under machining of the reduction-gear housing is presented in general by:

$$\begin{gathered}Đ(t)=e^{-2.517\cdot 10^{-3}\cdot t};\\ \begin{cases}P(t)=1.00;P(t)=0.99;P(t)=0.95;\\ P(t)=0.90;P(t)=0.80;P(t)=0.50.\end{cases}\end{gathered} \tag{32}$$

The limit values of the machining time that is inversely proportional to the cutting modes (feed and rotary speed) are set by the results of calculations in Mathcad: for $P(t_\gamma)$ = 1 $[t_0]$ = 0 min; for $P(t_\gamma)$ = 0.99 $[t_0]$ = 3.99 min; for $P(t_\gamma)$ = 0.95 $[t_0]$ = 20.38 min; for $P(t_\gamma)$ = 0.9 $[t_0]$ = 41.87 min; for $P(t_\gamma)$ = 0.8 $[t_0]$ = 88.67 min; for $P(t_\gamma)$ = 0.5 $[t_0]$ = 275.43 min (Fig. 8).

It is necessary to consider in optimizing the cutting modes [31] that the increase in the rotary speed and feed reduces the machining time. The metal-cutting tool resistance also decreases under such conditions [21, 45].

The calculations were performed for $P(t_\gamma)$ = 0.99 and $[t_0]$ = 3.99 min (Fig. 8).

Condition (26) is fulfilled according to table 1 and Fig. 8:

$$t_{0\ 005}=1.48<\left[t_0\right]=3.99\ \text{min.}$$

The following cutting modes are accepted for the selected mode of the technological process during milling of a basic plane in operation 005 for machining the reduction-gear housing according to the technical documentation: t = 3 mm; $S_{min.pasp.}$ = 200 mm/min; $n_{pasp.}$ = 125 min^{-1}, the calculated length of the working stroke of the metal-cutting tool $L_{mach.st.}$ = 296 mm [21].

To provide the specified gamma-percentile ope-rating time to failure $P(t_\gamma)$ = 0.99 for the limit machining time $[t_0]$ = 3.99 min, the limit value of the feed per minute is determined by (29):

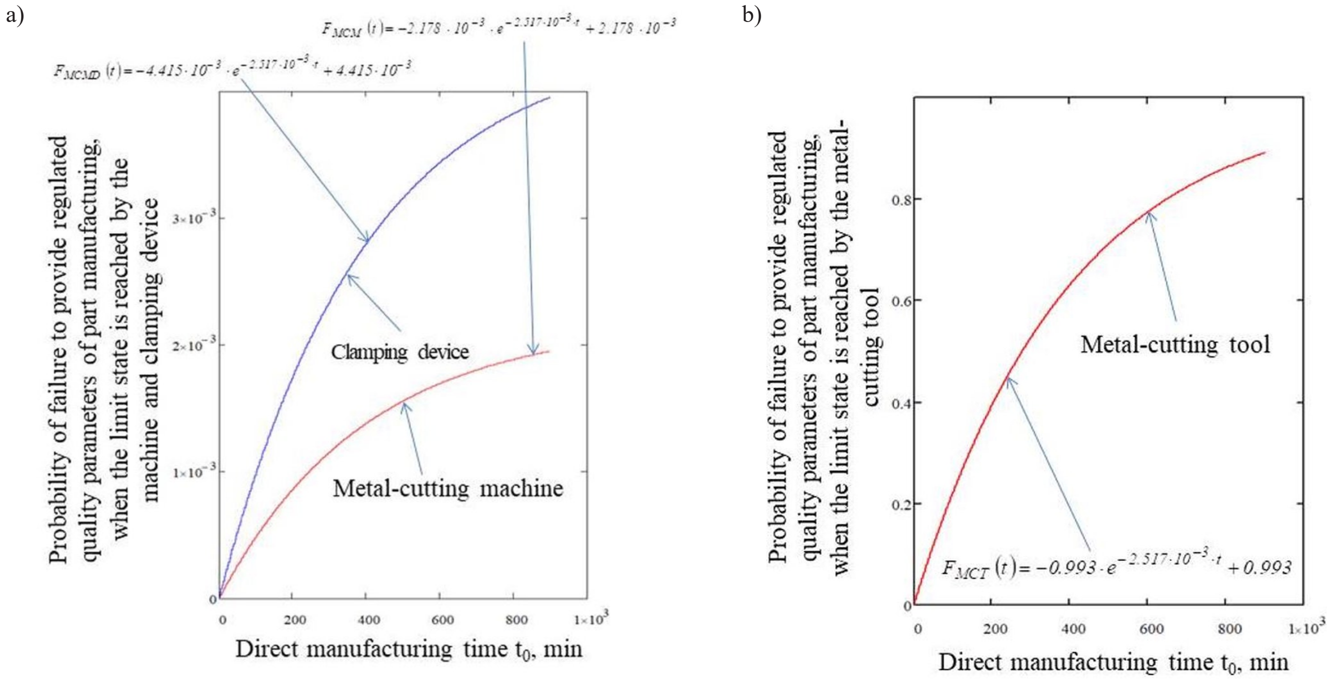

Fig.8. Probabilities of failure to ensure the regulated quality parameters at operation 005 machining of the reduction-gear housing when the limit state is reached: a) for metal-cutting machine and clamping device, b) for metal-cutting tool

$$\left[S_{\text{min. pasp.}}\right] = L_{mach.st.}/\left[t_0\right],$$
$$\left[S_{\text{min. pasp.}}\right] = 296/3.99 = 74.19 \text{ mm/min.} \tag{33}$$

Fulfilment of condition (31) according to the results (33) is provided by the nearest more certificate value $S_{min.pasp.}$ = 80 mm/min and the following (ascending) value of a feed rate for the horizontal milling machine used in operation 005.

In particular, for operation 005 in the technological process of manufacturing of the reduction-gear housing $S_{min.pasp.}$ = 200 mm/min that provides the fulfilment of condition (32):

$$S_{\min.nacn.} = 200 \ S_{\min.\ddot{\imath}\,\grave{a}\tilde{n}\ddot{\imath}.} = 200 \text{ mm/min} \ . \ \geq \ \left[S_{\min.}\right] = 74.19 \text{ mm/min.}$$

7. Conclusions

The main conclusions have been drawn based on the research results:

The process of providing the reliability for the metal-processing technological system in a certain specialised operation of the technological process of a workpiece manufacturing is checked by optimiz-

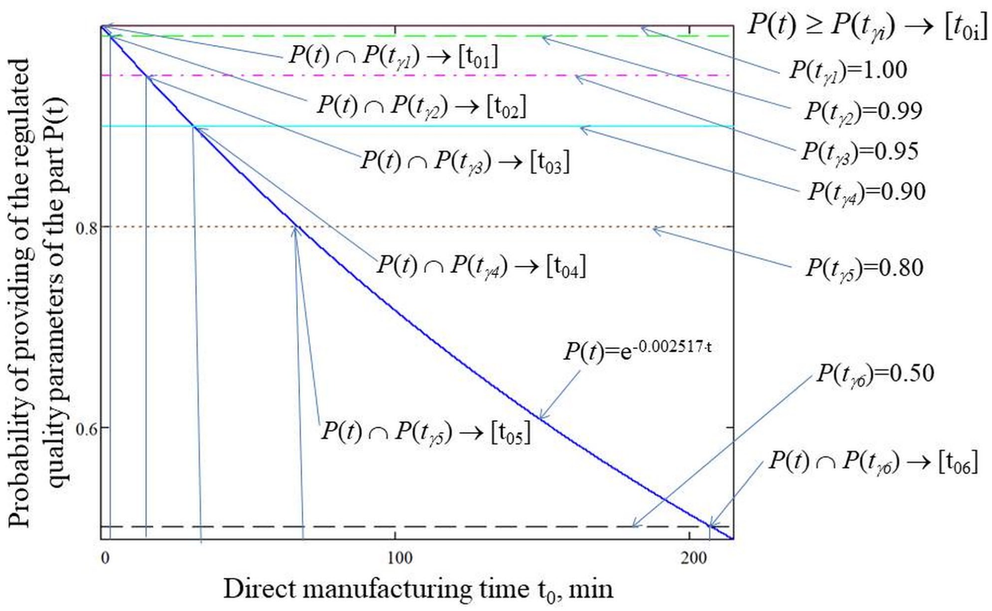

Fig. 9. Checking the condition of ensuring workability of a workpiece according to the regulated reliability parameters (gamma-percentile operation time to failure (t_γ)) in technological operation 005 of machining of the reduction-gear housing

ing the failure rate of the metal-cutting machine, clamping device, metal-cutting tool and rational choice of cutting modes. The process of providing the reliability for the elements of the technological system at a specific technological step during the workpiece manufacturing is checked by optimizing of the failure rate of the metal-cutting tools and rational choice of cutting modes. An increase in the rotary speed and (or) feed rate reduces the machining time and increases the probability of providing regulated quality parameters of the part workpiece. However, the intensification of the cutting modes of the workpiece surfaces reduces the tool life. It increases the probability of failure to provide regulated quality parameters of the workpiece when the metal-cutting tool reaches its limit state.

Optimization synthesis of parameters of manufacturing processes improves manufacturing efficiency, guarantee processing quality, prolongs the life of cutting tools, reduces the consumption of energy resources and all this adds value to the production process. In addition, the method is open for further modelling and optimization.

After testing the developed methodology, it was found that in terms of reliability, the metal cutting tool is the weakest element in the process media „machine-clamping device-cutting tool" and has the greatest influence on the formation of adjustable quality parameters of the machined parts. Meanwhile, metal cutting machine has the least impact on the quality parameters of the machined parts in the technological system.

Finally, the proposed optimization technique during the manufacturing of parts has been successfully integrated and tested in the real industry. As a result of optimization of cutting modes of the technological operation 005 (horizontal-milling) to manufacture the reduction-gear housing, the limit value of direct manufacturing time and feed per minute are $[t_0]$ = 3.99 min and $[S_{min.}]$ = 74.19 mm/min, respectively for the regulated gamma-percentile operation time to failure $P(t_\gamma)$=0.99. Rational cutting modes for this technological operation provide working capacity according to technical requirements.

Acknowledgment

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