

Investigation of the technological damageability of castings at the stage of design and technological preparation of the machine Life Cycle

Y M Kusyi and A M Kuk

Lviv Polytechnic National University, Mechanical Engineering Department, Stepan Bandera str., no. 12, 79013 Lviv, Ukraine

E-mail: jarkym@ukr.net

Abstract. Solution of the problem of machines reliability requires new approaches which at the present stage of machine-building industry development is realized by implementing PLM - concepts (Product Lifecycle Management). The PLM - concepts are the system of management of the machine parts life with design of the functionally-oriented technologies of production by means of parallel engineering.

Complex conditions of the products exploitation and complex technological processes of treatment require their profound theoretical and experimental investigation. An important task in the mechanical treatment and operation of products from the standpoint of their reliability is to predict their behavior at a certain point of time.

The LM-hardness method developed under the guidance of academician A.A. Lebedev to control the samples structure quality and materials damageability in the investigated part of the samples is proposed. According to the LM-hardness method derivatives of the physical parameters absolute values, for example, dissipation of the obtained control results carried out by the same devices in identical conditions serve as the evaluation criterion.

Homogeneity is a parameter that integrally describes the material state when processing the results of hardness control. The homogeneity is described by the Weibull coefficient m and the known Gumbel formula.

In our researches we propose to evaluate the analysis of the material structure state both by means of the Weibull coefficient m , and its technological damageability W , which is inversely proportional to the Weibull coefficient.

The experimental researches were carried out on aluminium alloy castings in sand moulds. Distribution of the technological damages W by the height of castings is established on the basis of performed researches at the stage of process engineering. The influence of the parameters of the "Sandvik" company tool design in treatment, using the "HAAS" treatment equipment on the change of the Weibull coefficient m is analyzed.

1. Statement of the problem

Ensuring technical specifications and minimum manufacturing cost of the machine parts is rational criteria of the technological process design. The reliability parameters which occur during parts exploitation are usually disregarded [1-6].

The problem of reliability is complex, since the reliability indicators are laid when designing the products, manufacture of parts and are realized in the operation of products. Infallibility, durability,



repairability and preservation are related to all substages and stages of the life cycle of the product in particular and machines on the whole (Figure 1) [6].

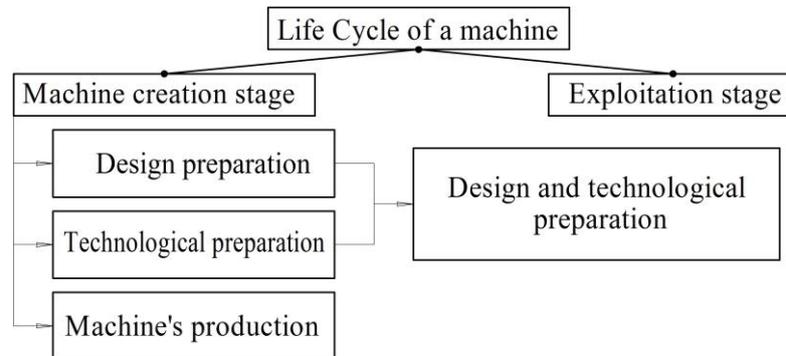


Figure 1. Stages and substages of Product Lifecycle

Modern researches in the field of reliability are carried out in two directions. The first direction involves computer modelling by means of the CAD/CAM/CAE systems. This direction is implemented in radioelectronics and other fields. The second direction is developed in mechanical engineering. The nature of physical processes is investigated, using the PMD procedures that ensure the reliability of the machine [7].

Since 1970s these directions have been combined with the transfer of rational ideas from one field to another and the formation on this basis a uniform science about reliability.

Solving the problem of machines reliability requires new approaches that at the present stage of the mechanical engineering development, is realized by the introduction of PLM - concepts (Product Lifecycle Management). The PLM - concepts represent a system of Life Cycle product management with the design of the functional-oriented technologies by means of parallel engineering.

For last 30 years the term “Product Life Cycle Management” has evolved in a new business-approach to managing all information about the product, including the creation, support, dissemination and use of this information throughout the Product Lifecycle in mechanical engineering industry.

The PLM concept is a solid foundation for the successful development and launch of new products and parts on the market . It combines information and people in order to organize their effective work [8].

The integrated solution of the PLM has such decisive capabilities [8]:

1. management of the entire Product Life Cycle – from initial planning to recycling. The rational PLC Management improves productivity and significantly reduces the cost of service and support of the product;
2. consolidation of all participants of the process of the machine parts creation, thus forming the interaction environment for support of all information on products and projects;
3. improvement of the exchange of information between product, quality and fixed assets to create close links between the technological process of the product manufacturing, production, quality analysis and service;
4. improvement of the the decision-making processes by means of enterprises portal, analytics and databases.

Planning, performing experimental researches and their analysis are the priority tasks for the effective implementation of the PLM-concepts in the practice of mechanical engineering.

2. Literature survey

The technological process has a direct and important influence on the reliability indicators. However, these bonds are complex, multi-stage and also not obvious (Figure 2) [3-5], [7].

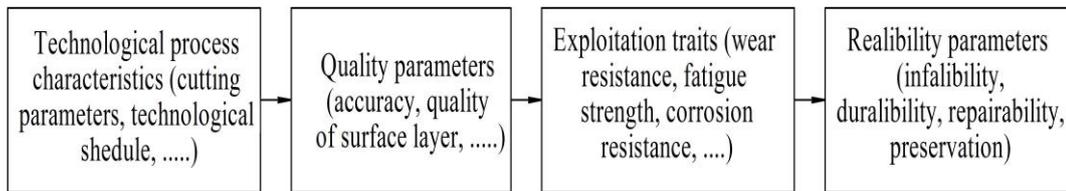


Figure 2. A chart of the dependence of reliability parameters on the technological process level [7]

It is established that about 80% of all defects found during production and use of products are due to the insufficient quality of the processes of developing the product concept and preparation of its production. The reason for about 60% failures that arise during the warranty period of the product is false, hasty and incomplete development, as well as non-compliance with the technical requirements [4-6].

Therefore, the ISO 9001: 2008 Standard focuses on the process (system) approach to the organization and management of work, the integration of all actions (operations) by shifting the center of importance from the function to the process that ensures the unity of management, improvement of organizational culture and allows the effective implementation of PLM - technology [4-6].

Modern theory of reliability is based on the fundamental laws of mathematics and natural sciences [6].

When providing quality indicators, an important role is played by heredity (Figure 3) - the transfer of properties of the object being processed (workpieces) from the previous stages of design to the next, which is reflected in the performance characteristics of the final product [9].

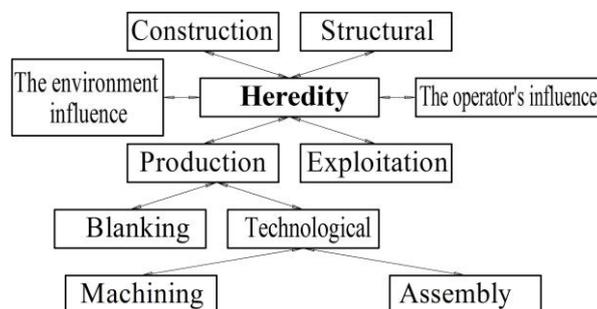


Figure 3. Types of heredity in the Life Cycles of the machines

A blank (casting, forging, press forming...) is the initial link of technological process. However, the role of blanking operations is not sufficiently taken into account when the influence of technological heredity on the quality parameters of the final product is analyzed [4], [9]. The performed researches [10] showed that the structure and properties of blanks were closely related to the heredity of liquid metal alloy. Only 25 % properties of the charge are transferred to the blank during machining, and 75 % is formed during the pouring and curing of the alloy under cooling.

Behaviour of castings without plastic deformation during technological machining and exploitation is determined by the structure which has been deformed after primary crystallization and total metal cooling.

The development of modern mechanical engineering is characterized by an increase in the role of providing project stages with information on the properties and behavior of materials under certain technological regimes for their machining and exploitation. This requires the development and implementation of the methods of computer modeling of material properties, structure and their machining, as well as interpretation of the conversion into CAE computer models. It should be noted that the relationship between the factors influencing the quality of products and their behavior in operation at the level of mathematical models is not fully developed, which complicates computer design [9].

At all stages of the machine Life Cycle in integrated CAD/CAE/CAM/PLM operating environments there is a need to consider and analyze the behavior of materials [11], review the questions about the joint design of materials and mechanical engineering parts [1].

Modern methods of foundry technologies modeling allow us to calculate accurately the temperature fields and predict shrinkage defects in castings. But existing software can not reliably determine the fracture zones in casting alloys, considering the factors that affect the initiation and propagation of cracks, the process of accumulation of damages and the formation of cracks in the mold materials. In this regard, theoretical and experimental investigations are necessary to clarify the mathematical models and programs [9].

The multi-stage process of metal failure includes the following stages [12–15]:

1) damage accumulation and breaking of the material continuity in the region of stresses and deformations;

2) development of microcracks in the environment with defects;

3) growth of cracks and separation of the material under loads and displacements set at the boundaries of the blank.

The technological damageability W in a majority of investigations of causes of material fracture during exploitation is not associated with structure. Only with the use of energy approaches to describe the processes of accumulation of damage [16], [17] it is considered that as a result of viscoplastic deformation, two types of microdamages develop - along the body and along the grain boundaries.

Internal variables that determine the processes of damage accumulation are scalar parameters - the energy of damageability along the grain body W_p and the energy of damage along the grain boundaries W_n [9]:

$$W_k = \int_0^t w_k, \quad k = p, n. \quad (1)$$

The damageability W_k depends on the history of viscoplastic deformation of the material. Damageability along the body and along the grain boundaries is characterized by the relative damage parameters W_p and W_n , respectively:

$$\begin{aligned} 0 \leq W_p \leq 1, \\ 0 \leq W_n \leq 1 \end{aligned} \quad (2)$$

Total damageability of the material W :

$$0 \leq W \leq 1. \quad (3)$$

Increase in damageability [9]:

$$\Delta W = dW_n + dW_p \quad (4)$$

where $dW_n = dW_n(T, W_n, W_p)$, $dW_p = dW_p(T, W_n, W_p)$.

Total increase in damageability:

$$\begin{aligned} \Delta W &= dW_n + dW_p, \\ \Delta W_n &= \Delta W_{nR} + \Delta W_{n\delta}, \\ \Delta W_p &= \Delta W_{pR} + \Delta W_{p\delta}, \end{aligned} \quad (5)$$

where ΔW_{nR} , $\Delta W_{n\delta}$ are the increments of the grain-boundary damageability due to viscoplastic deformation and as a result of changes in the conditions of deformation, respectively; ΔW_{pR} , $\Delta W_{p\delta}$ are the increments of intragranular damageability, respectively, due to viscoplastic deformation and as a result of a change in the type of the stress state and temperature.

Formation of technological damages during blanking operations, in particular foundry operations, their development during machining and exploitation and change in reliability of machine parts and machines under these conditions have not been adequately investigated.

3. Methods of research

The methods of assessing the degree of material damageability during the operating time by the results of direct (methods of metallography, weighting etc.) and secondary (acoustic emission, ohmic resistance etc.) measurements of the metal mechanical properties without fracture are known [16].

Application of these methods for assessing the material degradation as a result of damage accumulation during operating time leads to significant errors. This is due to the fact that the connection between the measured parameters and the characteristics of the structural state for a wide class of materials is ambiguous and it is difficult to make samples.

Assessment and analysis of the structure physical heterogeneity, damageability of various zones of castings are carried out using the LM-hardness method, developed under the guidance of academician A.A. Lebedev. According to this method the degree of dispersion of material mechanical characteristics after operating time at various stress levels is accepted as a parameter of damageability. The scattering of the measurement results performed by identical devices and identical conditions is more representative regarding the correlation of the mechanical properties of the material and the structure state than the absolute values of the characteristics. This method is most easily implemented, using mechanical characteristic of hardness, whose value is used for indirect evaluation of the material properties [4], [6], [9], [16], [17].

Homogeneity is the parameter that integrally characterizes the state of the material when processing the results of hardness measurements and is estimated by the Weibull coefficient (m). A large value of the coefficient m corresponds to a low level hardness dispersion and a low damageability degree; for the lower value, on the contrary, the damageability degree is higher [16], [17].

The Weibull homogeneity coefficient (m) is calculated by [16], [17]:

$$m = \frac{d(n)}{2,30259 \cdot S(\lg(H))}, \quad (6)$$

where $d(n)$ is a parameter that depends on the number of measurements, n ;

$$S(\lg(H)) = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^n (\lg(H_i) - \overline{\lg(H)})^2}, \quad (7)$$

$$\overline{\lg(H)} = \frac{1}{n} \cdot \sum_{i=1}^n \lg(H_i). \quad (8)$$

The technological damageability W is calculated by [9]:

$$W = \frac{m_{\max} - m_i}{m_{\max}}, \quad (9)$$

where m_i is the value of the Weibull coefficient on the i -th measurement line (plane); m_{\max} is the maximum value of the Weibull coefficient for a series of measurements.

The reliability coefficient $P(t)$ of the technological process will be described by formula..... [3], [6]:

$$P(t) = \prod_{i=1}^m [1 - (1 - P_0) \cdot (1 - P_{x_i}) \cdot (1 - P_k)], \quad (10)$$

where $P_0(t)$, $P_{x_i}(t)$ is the reliability coefficient during blanking and intermediate operations, P_k is the reliability coefficient in control operations.

From the position of the theory of probability [18]:

$$P(t) + W(t) = 1, \quad (11)$$

where $W(t)$ is failure of the machine part during it machining and exploitation.

With account of (11) Equation (10) is written as:

$$W(t) = \prod_{i=1}^m [1 - W_0 \cdot W_{x_i} \cdot W_k], \quad (12)$$

where $W_0(t)$, $W_{xi}(t)$ is the probability of failure during blanking and intermediate operations, W_k is the probability of failure in control operations.

4. Planning of experimental researches

4.1. Experimental samples

For experimental research, the blank was casted in a sand mold. The blank dimensions were 165x155x20 mm. The mold was made of material AK21M2.5H2.5 State standard-GOST 1853-93 (Table 1).

Table 1. Chemical composition of the material AK21M2.5H2.5 GOST 1853-93

Chemical element	Fe	Si	Mn	Ni	Cr	Ti	Al	Cu	Pb	Mg	Zn	Sn
Mass fraction, %	to 0.91	20.5	0.2 - 0.4	2.2 - 2.8	0.2 - 0.4	0.1 - 0.3	74.9 - 69.5	2.2 - 3.0	to 0.04	0.2 - 0.5	to 0.2	to 0.01

The technological process of casting is presented in Figure 4.

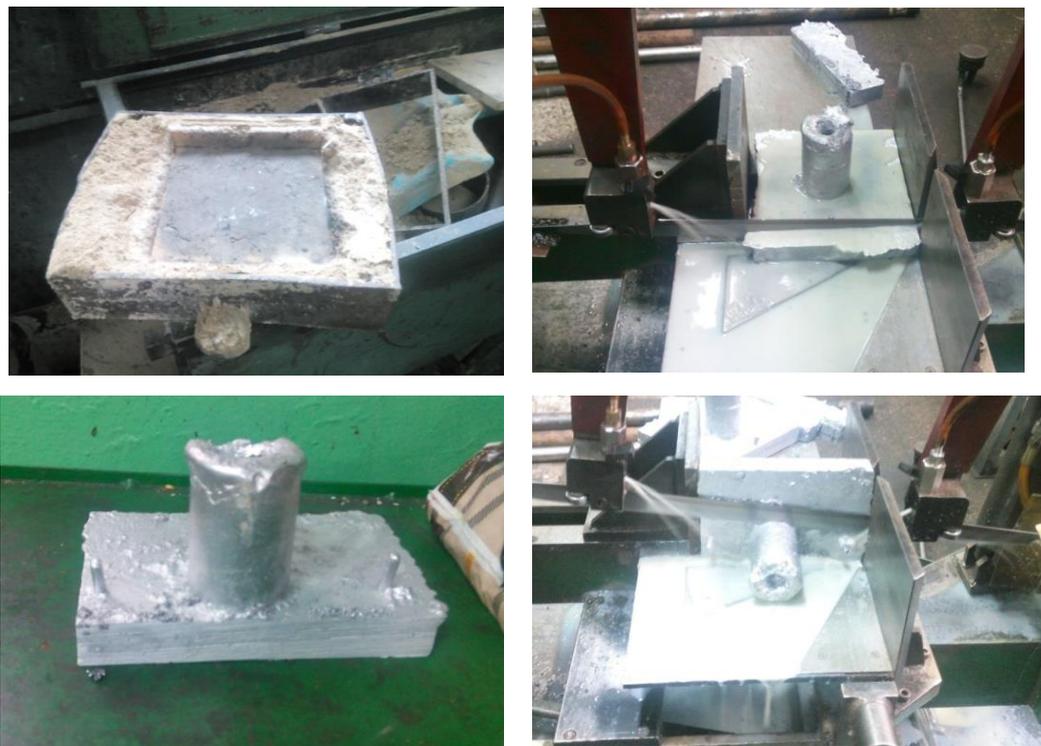


Figure 4. The technological process of casting

4.2. Machine-cutting tools and equipment

Cutters of different types are used for the plane machining. The planes of machine parts are often machined by cutters of the “Sandvik” company. Their advantages: vibration resistance, flexibility, variable depth of a scob groove, the angle of the scob groove lifting -50° .

The casting was machined by the end milling of “Sandvik” cutters. Four instruments for preprocessing and four instruments for semipreprocessing of diameter $\varnothing 6$ mm, $\varnothing 8$ mm, $\varnothing 10$ mm, $\varnothing 12$ mm were used (Figure 5).



Figure 5. The end “Sandvik” cutters:

- 1 - \varnothing 6 mm (1P240-0600-XA 1630); 2 - \varnothing 8 mm (1P240-0800-XA 1630);
 3 - \varnothing 10 mm (1P240-1000-XA 1630); 4 - \varnothing 12 mm (1P240-1200-XA 1630)

CNC machining centres are often used for machining of the parts in modern mechanical engineering.

Experimental sample was machined on the machine tool HAAS MINIMILL by milling (Figure 6).



Figure 6. Machine tool HAAS MINIMILL

4.3. Cutting parameters

Two series of experimental researches were planned. At first the surface of the experimental sample was milled by all four end milling cutters for semipreprocessing and measuring the hardness. After that the surface of the experiment sample was milled by all four end milling cutters for preprocessing and control of the hardness. The cutting parameters are shown in Table 2.

Table 2. Cutting parameters

Diameter of the end milling cutter, mm	Rotary speed n, min ⁻¹	Cutting speed V, m/min	Feed per teeth S _z , mm/teeth	Cutting depth t, mm
6	3100	58.4	0.1	3.0
8	4000	100.5	0.1	3.0
10	5800	182.0	0.1	3.0
12	5800	218.6	0.1	3.0

Milling of the experimental sample is presented in Figure 7. The experimental sample after cutting is shown in Figure 8.



Figure 7. Milling of the experimental sample



Figure 8. The experimental sample after cutting

4.4. The measurement device

The hardness was measured on the device TP-5006 (Russia) (Figure 9) using a ball $\varnothing 3.175$ mm under loading 588.4 N. In each experiment 30 measurements were performed. The blank after measurement of the hardness is presented in Figure. 10.



Figure 9. The device TP-5006 (Russia)

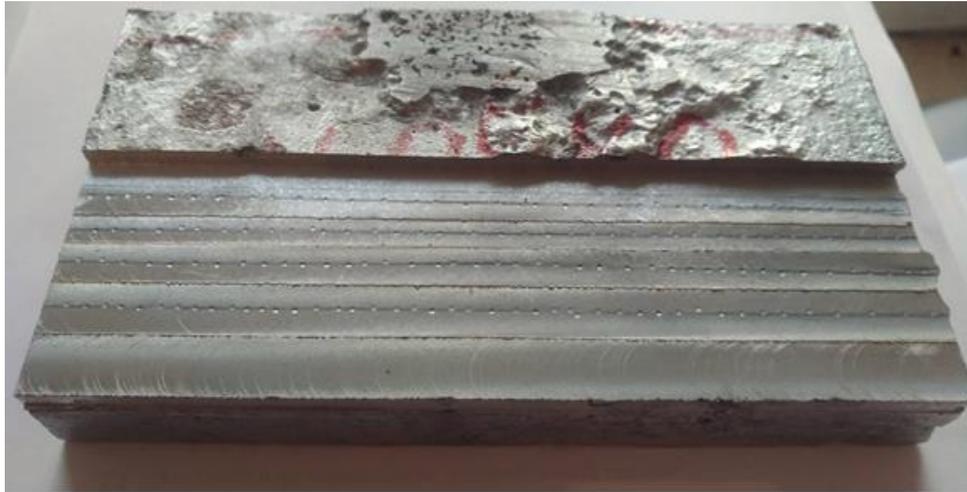


Figure 10. Blank after hardness measurements using device TP-5006 (Russia)

5. Analysis of the experimental results

The Weibull homogeneity coefficient (m) and the technological damageability W are calculated by equation (6), (9) in Mathcad 15 medium using the research results (Tables 3, 4). The diagrams $m=f(d)$ and $W=f(d)$ are presented in Figure 11.

Table 3. The value of the Weibull homogeneity coefficient (m) after two series of experimental researches

Diameter of the end milling cutter d , mm	The Weibull homogeneity coefficient (m)	
	after the first machining	after the second machining
6	51.70	63.11
8	46.98	66.84
10	25.26	63.34
12	18.15	34.42

Table 4. The value of the technological damageability W after two series of experimental researches

Diameter of the end milling cutter d , mm	The technological damageability W	
	after the first machining	after the second machining
6	0.23	0.06
8	0.3	0
10	0.62	0.06
12	0.73	0.49

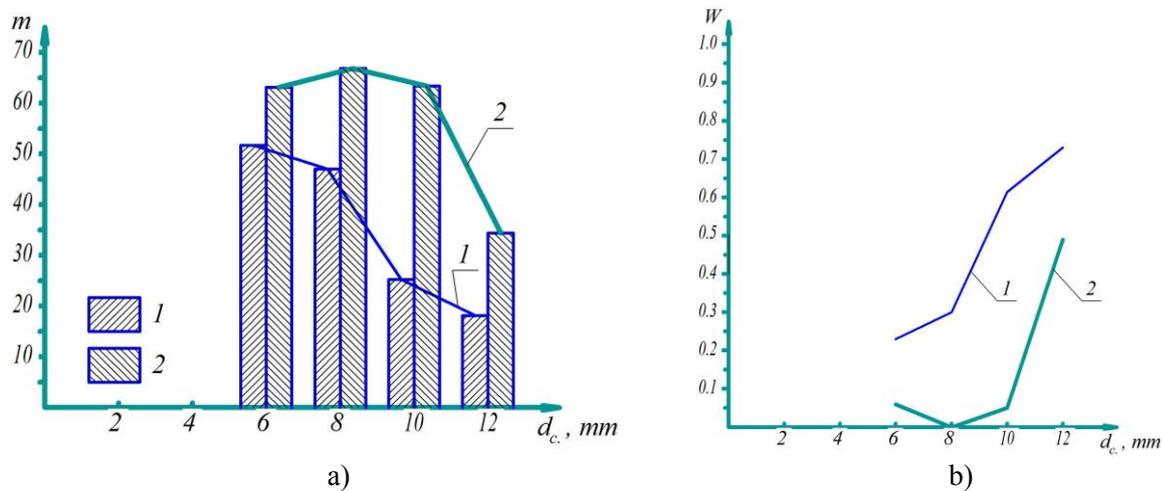


Figure 11. Dependence of the Weibull homogeneity coefficient (m) (a), technological damageability W (b) on the diameter of the end milling cutter; 1 - after the first machining; 2 – after the second machining

Figure 11 shows that the increasing diameter of the end milling cutter (increasing rotary speed n , cutting speed V) with the same feed per teeth and cutting depth leads to a decrease in the Weibull homogeneity coefficient (m) and increase in the technological damageability W after the first machining. After the second machining the Weibull homogeneity coefficient (m) increases further and stabilizes for the cutter of a diameter $\varnothing 6$ mm, $\varnothing 8$ mm, $\varnothing 10$ mm. The Weibull homogeneity coefficient (m) increases about twice for the end milling cutter $\varnothing 12$ mm.

The surface layer should be analyzed using the technological damageability W (b) when the distribution of the hardness over the sample height is known, in this case the surface layer should be analyzed by the value of the Weibull homogeneity coefficient. But in our case it is possible to use the parameter of technological damageability W even on two sections, since for the three of four types of sizes of the milling stabilization of the cutters measured values takes place.

The experimental research results show.

1. The maximum quantity of technological damages is typical of the zones of the surface layer at a depth up to 3 mm. The Weibull homogeneity coefficient (m) has the largest value and the technological damageability W has the minimum value for the end milling cutters of a diameter $\varnothing 6$ mm, $\varnothing 8$ mm. It is explained by the fact that teeth of these machine-cutting tools contacted with the surface layer t more often than the end milling cutters of diameter $\varnothing 10$ mm, $\varnothing 12$ mm.

2. At the depth of 3 to 6 mm the technological damageability values stabilize for the end milling cutters $\varnothing 6$ mm, $\varnothing 8$ mm, $\varnothing 10$ mm. This is proved by the increase in the Weibull homogeneity coefficient values (m) (decreasing values of the technological damageability W) and their approach to the cross-section with the quickest solidification of the melt. The technological damageability W decreases about twice for the end milling cutter $\varnothing 12$ mm.

3. The technological damageability can be used for the evaluation of the machine parts faultless operation.

6. Conclusions

The main conclusions have been drawn basing on the researches results.

1. The technological damages on the surface layers of the machine parts during blanking operations and after machining should be analyzed by the level of hardness dispersion.

2. For the first time the technological damageability W is proposed as a criterion for the machine parts reliability evaluation at the stage of machine design.

3. Further research should be carried out for a more wide nomenclature of machine parts and materials to introduce the proposed technique into the practice of modern mechanical engineering production.

References

- [1] 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
- [2] 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
- [3] Kusyj J M and Kuk A M 2015 Rozroblennya metodu vibracijno-vidcentrovogo zmicznennya dlya texnologichnogo zabezpechennya bezvidmovnosti detalej mashy`n *Eastern-European Journal of Enterprise Technologies* **1/7(73)** 41–51 in Ukrainian
- [4] Kusyj J M, Kuzin O A and Kuzin N O 2016 Vply`v texnologichnogo marshrutu obroblennya na formuvannya mizhzerennoyi poshkodzhuvanosti vy`ly`vkiv *Eastern-European Journal of Enterprise Technologies* **1/5(79)** 39–47 in Ukrainian
- [5] Kusyj J M, Kuk A M and Topilnytskyy V G 2018 Vibratory-centrifugal strengthening's influence on failure-free parameters of drilling pumps bushings. *Technology audit and production reserves* **1/1 (39)** 4–12
- [6] Kusyj J M and Topilnytskyy V G 2019 Influence of structural components placement on casting technological damages formation *Bulletin of the National Technical University "KhPI" (Series: New solutions in modern technology)* **5 (1330)** 41–47
- [7] Pronikov A S 1978 Nadezhnost' mashin. Moscow: Mashinostroenie, 592 in Russian
- [8] Zheleznyakova M S 2015 Konceptiya PLM - upravlenie zhiznennym ciklom produkta *Privolzhskij nauchnyj vestnik* **11(51)** 64–67 in Russian
- [9] Kusyj J M, Kuzin O A and Kuzin N 2017 Analysis of technological damageability of castings manufactured in sand molds *Technology audit and production reserves*. **3(1)** 17–23
- [10] Bozhydarnik V V, Hryhorieva N S and Shabaikovykh V A 2006 *Tekhnolohiia vyhotovlennia detalei vyrobiv*. Lutsk: Nadstyria, 612 in Ukrainian
- [11] Wang L 2013 Data Representation of Machine Models. *Dynamic Thermal Analysis of Machines in Running State* London Springer-Verlag 11–29
- [12] Durham S D and Padgett W J 1997 Cumulative Damage Models for System Failure with Application to Carbon Fibers and Composites. *Technometrics*, **39 (1)** 34–44
- [13] McEvily A J 2002 Metal failures: mechanisms, analysis, prevention John Wiley & Sons 324.
- [14] Zohdi T I and Wriggers P 2005 An introduction to computational micromechanics. Springer 198
- [15] Kundu T 2008 *Fundamentals of fracture mechanics* CRC Press Taylor and Francis Group Boca Raton FL USA 304
- [16] Lebedev A A, Muzyka N R and Volchek N L 2003 Metod diagnostiki sostoianii materiala po parametram rasseianiiia harakteristik tverdosti *Zavod. lab* **12** 49–51
- [17] Lebedev A A 2003 A new method of assesment of material degradation during its operating time *Zaluzhnyi Transport Ukrainy* **5** 30–33
- [18] Hansen N R 2005 *Probability theory and statistics*, Department of Applied Mathematics and Statistics University of Copenhagen 66