

This study considers a tool rejection system in mechanical engineering production with a single or small-batch type.

The task addressed is to substantiate assessment of the degree of wear of replaceable carbide inserts that are rejected during single and small-scale production based on the results of current diagnostics. The proposed approach could make it possible to track possible failures or premature rejection and unjustified losses based on a qualitative analysis of actual wear using probabilistic-stochastic methods.

A method for assessing the condition of rejected carbide inserts has been proposed, underlying which is measuring their wear on the back surface, transition to dimensional wear, their statistical processing and grouping by wear level.

Experimental studies were conducted on carbide inserts used in a milling cutter during roughing of steels under conditions of cyclic shock loads. It was found that the magnitude of dimensional wear obeys the normal distribution law with the following characteristics: mean value $\bar{h} = 0.08145$ mm, dispersion of scattering $D(h) = 0.00135$ mm², and mean square deviation $\sigma(h) = 0.0375$ mm. Dependences were derived and the percentage composition of rejected inserts was determined: 50.91% of inserts can still be used (with different resources); 1.17% of inserts are excessively worn (which could lead to defects); and 47.91% of inserts are correctly rejected during production.

The proposed methodology could be practically applied without complex measuring equipment and specialized monitoring systems, which makes it suitable for implementation during single and small-scale production. Implementing the method makes it possible to reduce unjustified rejected tools, increase the efficiency of the diagnostic system, and ensure the economy of material resources of an enterprise

Keywords: average insert resource, efficiency assessment, radial wear, statistical sampling

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DEVISING A METHOD FOR ASSESSING THE RESIDUAL RESOURCE AND EFFICIENCY OF TOOL UTILIZATION BASED ON THE ANALYSIS OF DIMENSIONAL WEAR

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1. Introduction

The main task of mechanical engineering is to manufacture machines (units, mechanisms, parts) of proper quality while enabling high productivity. The condition of the cutting tool is undoubtedly one of the most important components in ensuring the quality of the surfaces of the workpieces. Quality control (diagnostics of the condition) of the cutting elements of the tool is of great importance in production for their timely replacement or resharpening, which largely determines the future quality of the surfaces and the parts themselves. Timely detection and replacement of worn tools is important from the point of view of the quality of the machined surfaces. In addition, premature replacement of carbide inserts that have not exhausted their resource, taking into account the cost of one tool (or tool plate), increases

the cost of manufacturing the part, and accordingly, reduces competitiveness.

Therefore, research aimed at increasing the validity of cutting tool condition control and assessing the effectiveness of carbide insert rejection systems is relevant for modern mechanical engineering.

2. Literature review and problem statement

One of the key aspects in ensuring the reliability of the cutting process is the ability to correctly predict the durability of metal-cutting tools. In automated serial production, 63% of failures of technological processing systems are caused by the failure of the cutting tool [1]. Therefore, it is necessary to use additional systems that could predict or detect a worn cutting

tool in real time for its timely replacement. Research in this area can be divided into several directions. Some of them are focused on the theoretical prediction of the tool resource depending on the elements of the cutting modes, the type of material, etc. The main goal of such studies is to calculate the tool durability period. In [2], experimental tests were carried out to analyze the evolution of the wear pattern. A significant influence of the angle of the side cutting edge on the tool wear regime during finish turning of Inconel 718 was found. In [3], the influence of cutting modes on the wear of hard ceramic inserts during milling Inconel 625 was studied and the impact of feed and depth of cut on the tool life was predicted. The wear patterns and mechanisms were investigated using 9 tests designed according to the Taguchi L9 orthogonal array. The results showed that of all the parameters analyzed, the feed had the greatest impact on stability. Regression coefficients of the impact of all other process parameters on stability were derived. In [4], a universal wear model was proposed, based on the calculation of instantaneous cutting forces and the relationship of this parameter with the natural frequency and amplitude of oscillations at different stages of milling. A significant drawback of such models is often the inability to take into account the conditions of actual production and other unpredictable accompanying cutting processes. These models are most appropriate to use under conditions of mass and large-scale production.

One area of research is the processing of signals of various types for the detection of worn tools. For example, in [1] it is proposed to assess the degree of tool wear by cutting forces, and in [5] – by acoustic measurements. Temperature and acoustic methods as an indicator of cutting blade degradation are also proposed to be used in works [6, 7]. Work [8] considers the application of the method of detecting vibrations, self-excitation, and wear during high-speed milling; and in [9], the vibration method is used to detect tool wear during drilling. However, for example, excess cutting forces or additional presence of vibrations can be due not only to tool wear but also to the heterogeneity of the processed material, the presence of abrasive inclusions, etc. The same applies to acoustic and temperature methods. Therefore, in [10], a comprehensive methodology is proposed, which includes synchronous processing of signals from vibroacoustic systems, systems that measure cutting forces and vibrations. In [11], a method is devised that combines information from sensors of scattering flow signals and spindle-motor current using statistical and non-statistical time-domain parameters, which are then simplified using linear discriminant analysis (LDA). Next, a feedforward neural network is used to automatically classify the level of cutting tool wear. However, such methods significantly increase the cost of the monitoring system. Various diagnostic methods become part of the constructed digital model based on large-scale data analysis [12] and are included in the digital model of the enterprise [13], which is based on the probabilistic-statistical approach to process management.

Another direction is the use of visual inspection methods. For example, in [14, 15], machine vision was used to analyze the current state of the cutting edge of tools and their wear on the back surface. A continuation of those studies is paper [16], which devised a method that uses intuitive-fuzzy clustering of C-means (IFCM) for detailed segmentation of the wear area, which makes it possible to obtain a much clearer image of the tool wear zone. In work [17], raw data from sensors are processed, discarding random values, errors, etc. They are then used as input data for training algorithms to create models of wear of cutting tools. In studies [14–17], the problem of

a reasonable assessment of the state of an already rejected tool is practically not considered. They lack statistical analysis of the actual wear of the tool after its operation in order to detect premature or unjustified rejection.

Systems using intelligent analysis methods, in particular the use of deep learning methods, are evolving significantly. In [18], an artificial neural network (ANN) classifier was designed, based on statistical training of machining fluctuations in determining the wear of a turning tool. The built model could be used for single-edged cutting tools. In [19], a model based on an adaptive network-based fuzzy logic system (ANFIS) and a new method of statistical signal analysis, the *I-kaz* method, were developed. Although the correlation coefficients and average errors were in the range of 0.989–0.995 and 2.30–5.08%, the authors note that the accuracy of the models depends on the quality of the data obtained. In [20], the use of artificial neural networks as expert subsystems of cutting tool diagnostics systems is described. In [21], it is argued that the most promising areas are those based on machine learning and artificial intelligence. Such methods require the presence of additional, often expensive, measuring equipment on each machine, as well as processing of measurement results, and can be used in mass and large-scale production.

The inability to accurately predict the amount of wear, and therefore to replace the inserts in a timely manner, leads to two problems:

- 1) the insert wears excessively, which causes defects in the machining process of the part and the possibility of damage to the tool body, the cost of which is hundreds of times higher than the cost of the insert;

- 2) the stability of the dimensions of the insert allows the machining process to be performed but it is changed to place all the new inserts on the tool body.

This causes financial losses for the enterprise, increasing the cost of production.

Thus, despite the large number of approaches and models on the research topic, the issue of assessing the effectiveness of the functioning of the residual resource control system for carbide inserts, taking into account the stochastic nature of the cutting process and actual operating conditions, remains insufficiently studied. In some papers, the emphasis is on the accuracy of determining the wear of an individual tool. A large number of studies consider specifically the mass and large-scale production. However, the issues of statistical analysis of the actual use of the resource of the inserts, emphasis on their correct or premature replacement and quantitative assessment of the residual resource by the enterprise remain out of attention. This necessitates the research aimed at substantiating the assessment of the operation of the resource control system of multi-blade tools under production conditions based on probabilistic statistical analysis.

3. The aim and objectives of the study

The purpose of our study is to devise a method for estimating the residual life of carbide inserts for multi-blade tools based on a probabilistic-stochastic approach. This will make it possible to monitor and respond in a timely manner to the process of tool rejection under production conditions, save the company's resources on losses from rejecting excessively worn tool inserts (due to a probable shortage of products), as well as on insufficiently worn ones (by taking them into account in the cost of production).

To achieve the goal, the following tasks were set:

- to statistically process the results of the calculated dimensional wear of carbide inserts, obtained on the basis of measuring their wear on the back surface, to determine its variance characteristics and check the homogeneity of experimental samples;
- to establish and prove the law of distribution of the magnitude of dimensional radial wear;
- to quantitatively assess the effectiveness of the system for rejecting replaceable carbide inserts based on a statistical analysis of their dimensional wear.

4. Materials and methods

The object of our study is the tool rejection system in machine-building production with a single or small-batch type. During production, it is necessary to monitor the correctness of the rejection system – it is necessary to have a methodology that makes it possible to quickly and statistically reliably analyze how effectively the tool resource is used. The most effective way to determine this is to measure the wear of inserts rejected by production. Of course, it is impossible to measure the wear of all inserts during production, so it is necessary to apply probabilistic-statistical approaches.

Our principal hypothesis assumes that the actual dimensional wear of rejected replaceable carbide inserts is a stochastic value that obeys a certain distribution law, and a statistical analysis of a sample of such inserts makes it possible to assess the effectiveness of their rejection system with reasonable reliability. It was also assumed that the established distribution law is characteristic not only for the sample under study but also for the entire set of inserts rejected on tools of the same type under similar operating conditions.

Note that the study did not take into account the influence of individual technological and operational factors that could potentially change the nature of the wear distribution law.

For the research, the most common type of inserts by different manufacturers was selected. We measured the wear of carbide inserts marked APMT1604PDER-M2 AU1035G AGIR and APMT160408PDER-M YBG202 according to the ISO classification, used under actual production conditions on a Ø50.3 mm cutter with 4 such inserts working simultaneously. The front angle of the insert: $\gamma = 15^\circ$; $\alpha = 10^\circ$. One used insert was randomly selected from the cutter over a certain time.

Using an MBS-10 microscope, the wear on the back surface of the insert (which is marked h_b [17]) in the main cutting plane was measured (Fig. 1).



Fig. 1. Photograph of the measurement scheme: 1 – test insert; 2 – microscope; 3 – light source

The magnification of the microscope is 70 times. The microscope is equipped with a scale with a division value of 0.0143 mm at this magnification. The measurement accuracy

is 0.00715 mm. In this case, a certain number of inserts with chips were found – Fig. 2. They were not included in the statistical series but their percentage was taken into account in the final conclusions. Photographs of some worn inserts are shown in Fig. 3.

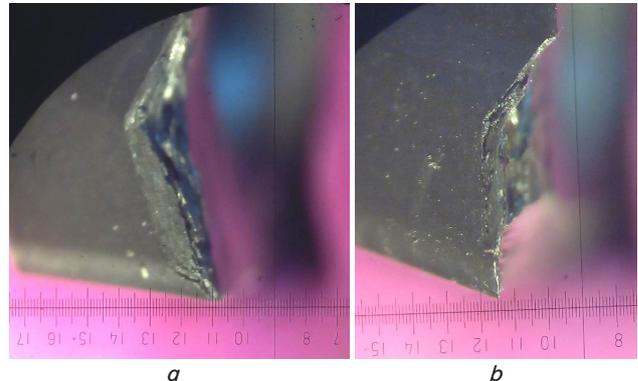


Fig. 2. Images of some inserts with chips: a – APMT1604PDER-M2 AU1035G AGIR; b – APMT160408PDER-M YBG202

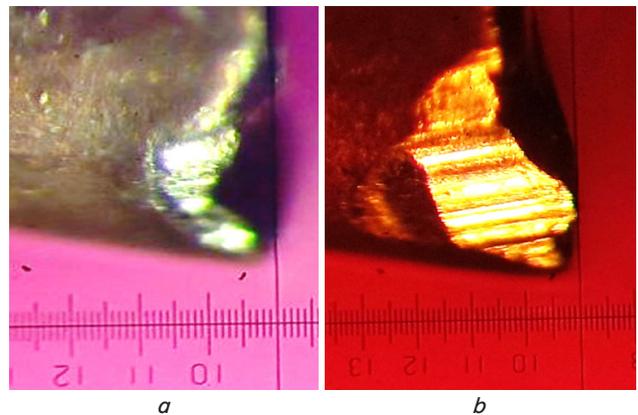


Fig. 3. Images of some worn inserts: a – APMT1604PDER-M2 AU1035G AGIR; b – APMT160408PDER-M YBG202

Using Fig. 4, the values of dimensional wear h for each of the inserts were determined based on the following considerations.

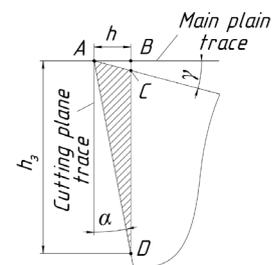


Fig. 4. Calculation scheme for determining the value of dimensional wear h

From $\triangle ABD$, we obtained: $AB = (BC + CD) / \text{tg}(90 - \alpha)$. From $\triangle ABC$: $AB = BC / \text{tg}\gamma$. We equated values of AB from $\triangle ABD$ and $\triangle ABC$

$$\frac{(BC + CD)}{\text{tg}(90 - \alpha)} = \frac{BC}{\text{tg}\gamma}$$

Solving for BC and substituting the value $CD = h_b$, we obtain

$$BC = h_b \cdot \operatorname{tg} \gamma / (\operatorname{ctg} \alpha - \operatorname{tg} \gamma),$$

where $\alpha < 45^\circ; \gamma < 45^\circ$.

The resulting value of dimensional wear is

$$AB = h = \frac{h_b}{(\operatorname{ctg} \alpha - \tan \gamma)}, \tag{1}$$

where γ, α are the leading and trailing angles of the insert in the main cutting plane (Fig. 4), respectively.

Thus, for each measured h_b value, the value of h was calculated according to (1), using the method described in [22]. Considering that the insert has two cutting edges, 2 dimensional wear numbers h were obtained from one insert (if one side had a chip, one value was used, if both sides had a chip, the value was discarded). Thus, 2 statistical series were formed: in the first series (for the APMT160408PDER-M YBG202 ZCC insert) – 55 values, in the second (for the APMT1604PDER-M2 AU1035G AGIR insert) – 64 values.

5. Devising a method for estimating the residual resource of carbide inserts of multi-blade tools based on probabilistic and statistical analysis of the magnitude of dimensional wear

5.1. Statistical processing of results of the calculated dimensional wear of carbide inserts

In general, the methodology for processing the measurement results reported in [22] was used. For both samples, the following scattering characteristics were found: average values \bar{h} (which are taken equal to the mathematical expectation $M(h)$), scattering dispersions $D(h)$, and mean square deviations $\sigma(h)$, which were calculated from the following formulas [23]:

$$\bar{h} = \frac{\sum_{i=1}^n h_i}{n}, \tag{2}$$

$$D(h) = \frac{1}{n} \sum_{i=1}^n (h_i - \bar{h})^2, \tag{3}$$

$$\sigma(h) = \sqrt{D(h)}, \tag{4}$$

where n is the sample size.

Further, according to the Grebs criterion [23] $t_k = \frac{|h'_i - \bar{h}|}{\sigma(h)}$ (here h'_i is

the value that stands out sharply), those values that stood out sharply were rejected. The rejected values were not taken into account in further samples.

Both samples were checked for homogeneity using the Student t (5) and Fisher F (6) criteria, using the following dependences:

$$t = \frac{|\bar{h}_1 - \bar{h}_2|}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}}, \tag{5}$$

$$F = \frac{D(h)_1}{D(h)_2}. \tag{6}$$

The calculation data are listed in Table 1.

According to the Student's test, it is proven that the samples are homogeneous with a probability greater than 92.03%. According to the Fisher test, the samples can be considered homogeneous since the obtained value of the criterion $F(1.421) < Ft(1.44)$.

Table 1

Scattering characteristics and calculations of sample homogeneity

Insert type	Mean value \bar{h} , mm	Dispersion of scattering $D(h)$, mm ²	Mean square deviation $\sigma(h)$, mm	Student's t -test t	Significance according to Student's t -test	Fisher's F test (tabular value of the test F_T)
YBG202	0.0831	0.0011	0.0342	0.0912	>0.9203	1.421 (1.44)
AU1035G	0.0798	0.0016	0.0408			

Given the homogeneity of the samples, they were combined into one, for which the scattering characteristics were calculated according to formulas (2) to (4), (Table 1).

The following values of the scattering characteristics were obtained for the combined sample: mean value $\bar{h} = 0.08145$ mm; scattering variance $D(h) = 0.00135$ mm²; mean square deviation $\sigma(h) = 0.0375$ mm.

5.2. Establishing the distribution law of the dimensional wear value

For the total sample, the sample data were divided into 8 intervals [23]. The experimental data of the dimensional wear value were grouped. The grouped data are given in Table 2. For this purpose, a typical statistical data processing methodology was used [24].

Based on the grouping, a histogram and a frequency polygon were constructed in Fig. 5. Taking into account the appearance of the histogram, as well as based on the Chebyshev theorem and the central limit theorem of probability theory, it was assumed that the random variable h obeys the normal distribution law with the previously obtained characteristics \bar{h} and $\sigma(h)$.

Table 2

Grouped dimensional wear data

No.	Interval	Mid-interval	Frequency of occurrence in the interval m_i	Relative frequency	Accumulated frequency of occurrence in the interval Nm_i	Accumulated relative frequency
1	0.0088–0.0333	0.0211	9	0.0756	9	0.0756
2	0.0333–0.0579	0.0456	21	0.1765	30	0.2521
3	0.0579–0.0824	0.0702	25	0.2101	55	0.4622
4	0.0824–0.1070	0.0948	38	0.3193	93	0.7815
5	0.1070–0.1315	0.1193	17	0.1429	110	0.9244
6	0.1315–0.1561	0.1439	5	0.0420	115	0.9664
7	0.1561–0.1807	0.1684	2	0.0168	117	0.9832
8	0.1807–0.2052	0.1930	2	0.0168	119	1

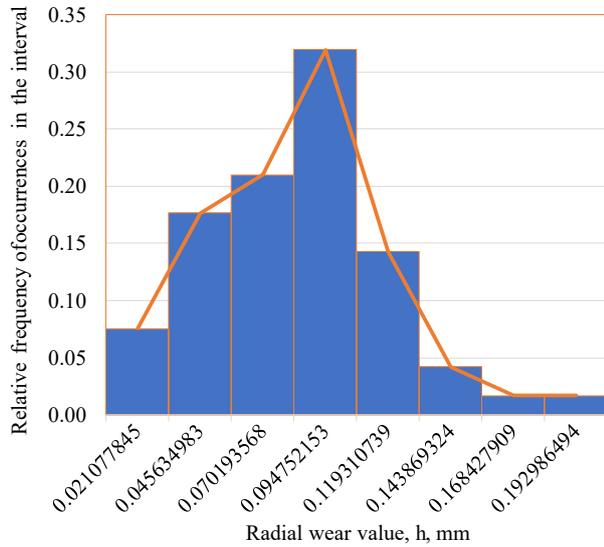


Fig. 5. Polygon and histogram of radial wear distribution

Substituting these data into the formula for the density of the normal distribution [24], we obtained

$$f(h) = \frac{1}{0.0377\sqrt{2\pi}} \cdot e^{-\frac{(h-0.0813)^2}{2 \cdot 0.0377^2}} = 10.582 \cdot e^{-\frac{(h-0.0813)^2}{0.00284}} \quad (7)$$

The resulting density distribution function was constructed (Fig. 6) using the calculation table (Table 3). For clarity, a frequency polygon was superimposed on the resulting density distribution curve.

The results were verified using the Pearson criterion. This is one of the most accurate criteria for checking the correspondence between the theoretical and experimental distribution laws. For this purpose, the χ^2 value was determined from the following formula [9]

$$\chi^2 = \sum_{i=1}^f \frac{m_i - m'_i}{m_i} \quad (8)$$

where m_i and m'_i , respectively, are the experimental and theoretical frequencies of occurrence in the interval; f – the number of combined intervals with the condition $m_i \geq 4$.

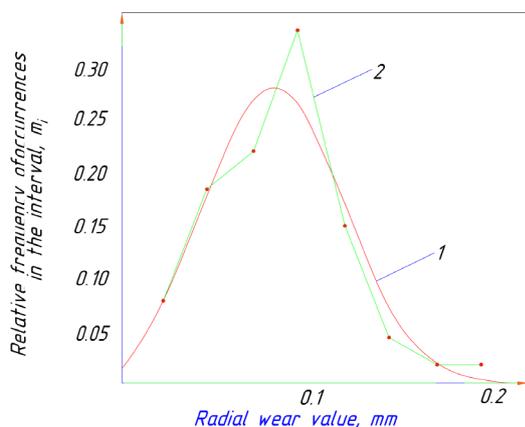


Fig. 6. Graphical representation of the density distribution of the radial wear value: 1 – theoretical density curve of the normal distribution; 2 – frequency polygon

Table 3

Calculation table of theoretical frequencies

In-terval No.	Interval from – to	Mid-in-terval	t_i	$\varphi(t_i)$	Theo-retical frequen-cy m'_i	Accu-mulated theo-retical frequen-cy
1	0.0088–0.0333	0.0211	1.5971	0.1200	9.2855	9.2855
2	0.0333–0.0579	0.0456	0.9468	0.2685	20.7747	30.0601
3	0.0579–0.0824	0.0702	0.2966	0.3894	30.1313	60.1914
4	0.0824–0.1070	0.0948	0.3536	0.3621	28.0212	88.2126
5	0.1070–0.1315	0.1193	1.0039	0.2178	16.8531	105.0657
6	0.1315–0.1561	0.1439	1.6541	0.0833	6.4449	111.5105
7	0.1561–0.1807	0.1684	2.3044	0.0208	1.6118	113.1223
8	0.1807–0.2052	0.1930	2.9546	0.0033	0.2553	113.3777

In Table 4, the theoretical m'_i and experimental m_i frequencies of occurrence in the interval are combined, adjusted taking into account the condition $m_i \geq 4$.

Table 4

Data for determining Pearson’s criterion

No.	Interval	m_i	m_i after correction	m'_i	m'_i after correction
1	0.0088–0.033356	9	9	9.2855	9.2855
2	0.0333–0.057914	21	21	20.7747	20.7747
3	0.0579–0.082473	25	25	30.1313	30.1313
4	0.0824–0.107031	38	38	28.0212	28.0212
5	0.1070–0.13159	17	17	16.8531	16.8531
6	0.1315–0.156149	5	5	6.4449	6.4449
7	0.1561–0.180707	2	4	1.6118	1.8671
8	0.1807–0.205266	2		0.2553	

Applying (8) yields

$$\chi^2 = \frac{(9-9.285)^2}{9.285} + \frac{(21-20.774)^2}{20.774} + \frac{(25-30.131)^2}{30.131} + \frac{(38-2.021)^2}{28.021} + \frac{(17-16.853)^2}{16.853} + \frac{(5-6.444)^2}{6.444} + \frac{(4-1.867)^2}{1.867} = 5.241.$$

The number of degrees of freedom $k = f - g - 1$ is determined, where f is the number of combined intervals, $g = 2$ for the normal distribution law. We obtain $k = 7 - 2 - 1 = 4$. Using [24], we get $0.2 < P(\chi^2) < 0.3$. Since $P(\chi^2) > 0.05$ according to the Pearson criterion, the obtained distribution law can be considered normal.

Considering that for analysis in the technique it is advisable to use not the normal distribution law with the limits $(-\infty; +\infty)$ but the truncated normal with the limits $\bar{h} \pm 3\sigma$, the scattering limits of parameter h are obtained: $h = \bar{h} \pm 3\sigma$; $h = 0.0814 \pm 3 \cdot 0.0378$; $h \in (-0.032; 0.1948)$. This is also visible on the plot of the distribution density function of quantity h (Fig. 6).

Given the technical limitation: namely, the value of h – radial wear – can only be positive, the density distribution function of the random variable h is obtained

$$f(h) = c \cdot 10.582 \cdot e^{-\frac{(h-0.0814)^2}{0.00284}}, \quad (9)$$

where $h \in (0; \bar{h} + 3\sigma(h))$; c – coefficient that takes into account the truncation in the law of normal distribution $c = 0.9973$ [25]. In this case, a theoretical assumption is adopted that an insert with zero wear can be rejected.

To take into account inserts with chips, the number of cutting blades without chips (processed) is set in the mathematical model as a percentage of the total number.

The number of cutting blades with chips is $k = 55$.

The total number of data is $m = n + k, m = 119 + 55 = 174$.

The number of worked cutting surfaces of the inserts is expressed as

$$g = \frac{n}{(n+k)} = 100 \cdot \frac{119}{(119+55)} = 0.6839 \cdot 100\% = 68.39\%.$$

Having adjusted the distribution density function (9) by the obtained coefficient $g = 0.6839$, which takes into account inserts with circles, we obtain

$$f(h) = g \cdot c \cdot 10.582 \cdot e^{-\frac{(h-0.0814)^2}{0.00284}}. \quad (10)$$

By substituting the known values of c and g obtained above into (10) and simplifying, we obtain the distribution density function for specific conditions

$$f(h) = 7.217 \cdot e^{-\frac{(h-0.0814)^2}{0.00284}}, \quad (11)$$

where $h \in (0; \bar{h} + 3 \cdot 0.0378)$.

The final plot of the distribution density function is shown in Fig. 7.

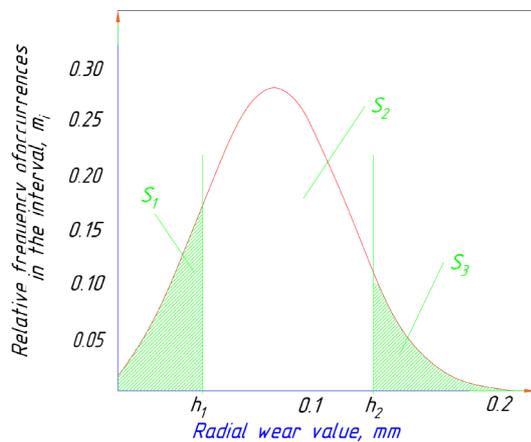


Fig. 7. Curve of distribution of the magnitude of radial insert wear

5. 3. Quantitative assessment of the system efficiency for rejecting replaceable carbide inserts

The area under the curve S_1 (up to the value of h_1) (Fig. 7) shows the percentage of inserts rejected by production that have not yet reached the end of their service life.

The area S_2 (between the values of h_1 and h_2) (Fig. 7) shows the percentage of correctly rejected inserts.

The area S_3 (to the right of the value of h_2) shows the percentage of excessively worn inserts, i.e., wear that can lead to a defect. To this percentage, it is necessary to add the percentage of inserts with chips.

The value of h_1 according to the recommendations for wear of cutting tools [3] is found as

$$h_1 = (1/4 \dots 1/3) \cdot IT,$$

where IT is the tolerance value for the size of the machined parts.

Considering that this tool is used at the enterprise mainly for roughing and must provide accuracy according to 12 quality [3] and is used in the size range of 40–60 mm (50 mm is assumed for calculations), the tolerance value is $IT = 0.25$. We get

$$h_1 = (1/4 \dots 1/3) \cdot 0.25 = (0.0625 \dots 0.083) \text{ mm}.$$

For practical calculations, the maximum permissible wear value $h_1 = 0.083$ was adopted.

The h_2 value according to the recommendations for cutting tool wear was found as

$$h_2 = 2/3 \cdot IT = 2/3 \cdot 0.25 = 0.167 \text{ mm}.$$

The S_1, S_2, S_3 areas are obtained by taking the h_1 and h_2 values as quartiles from the following dependences:

$$S_1 = \int_0^{h_1} f(h) dh, \quad S_2 = \int_{h_1}^{h_2} f(h) dh,$$

$$S_3 = \int_{h_2}^{\bar{h}+0.1134} f(h) dh.$$

We have: $S_1 = 0.34; S_2 = 0.32; S_3 = 0.078$.

Discarding the chipped inserts (taking the area under the distribution curve equal to 1), the following values were obtained: 50.91% – inserts can still be used; 1.17% – inserts that are excessively worn; 47.91% – correctly discarded.

The economic loss from the use per insert is determined from the following dependence

$$E = (C/2) \cdot S_1 \cdot k_{ave}, \quad (12)$$

where C is the cost of one insert (UAH); k_{ave} is the average coefficient of the service life of inserts that are recognized as suitable.

6. Discussion of the results of study of the magnitude of radial wear

The tool rejection system at a particular enterprise is the same for a certain type of tool, so taking rejected inserts from different tools, similar samples were expected. This was proven by the criteria for comparing samples (Student and Fisher) (Table 1). With sufficient probability (92.03%), the sample data are homogeneous, so they were combined into one. It was assumed that at the same enterprise with the same rejection system, the average values of the radial wear and dispersion would differ statistically insignificantly. Despite the fact that the DSTU ISO standard "Testing tool durability in milling – Part 2: Finish milling" (DSTU ISO 8688-2:1989)

contains a tool durability criterion, many researchers have redefined it in accordance with practical machining conditions, for example, the critical wear of the side of the tool was determined as 300 μm [8, 26] or 200 μm [15]. Other scientific sources do not indicate what the permissible wear value should be. Our results showed (Table 1) that the average value of the wear value was 1/3–1/4 of the tolerance on the size. This corresponds to practical recommendations, according to which the tolerance field of the tool is assigned for machining a specific surface.

The magnitude of radial wear depends on a large number of factors, described in particular in [1–3, 5, 8], among the most important of which are elements of the cutting mode, vibration, quality of the cutting material, etc. According to the central limit theorem, under reasonable conditions, when the number of components increases, the resulting distribution tends to Gaussian [27]. Grouping the dimensional wear data (Table 2) and constructing a polygon and a frequency histogram (Fig. 5) according to the Pearson criterion (8) and Table 4, it is proved that the magnitude of radial wear of inserts rejected by production obeys the normal distribution law ($P(\chi^2) > 0.05$).

The radial wear distribution curve (Fig. 7) shows three groups of worn inserts. The amount of rejected excessively worn inserts is 1.17%, which is a low figure and is lower than the 5% confidence level accepted in mechanical engineering. The large amount of insufficiently worn inserts (50.17%) is explained by the following considerations. As is known, inserts in milling cutters wear unevenly and if one is worn out, all of them have to be replaced to ensure machining accuracy. The tolerance on the inserts also affects the machining accuracy, since in a milling cutter with four inserts, each has a different runout (within its tolerance). For example, the studied inserts of class M accuracy have a tolerance on the size of ± 0.013 mm. Theoretically, in the same milling cutter, one insert can have a runout of 0.026 mm more than the other. Accordingly, it wears out faster and reaches its critical wear (according to the method described in [7] – by exceeding the cutting forces, or by the method of acoustic diagnostics [1]), and other inserts may still have a significant resource.

In addition, a significant number of inserts with chips were found. Under conditions of single production when each time it is necessary to work out the technology, assign cutting modes (often under conditions of complete absence of reference information), tool chips often occur. In this study, the average value of chips in two samples was taken (according to the results – 31.61%). In order to statistically reliably take into account the percentage of chipped inserts, additional research is necessary. To a large extent, the number of chips depends on the qualifications of the technologist-programmer, as well as on the quality of the tool itself.

The features of the proposed method are as follows. The production manager needs to periodically check the inserts rejected by production by measuring their wear on the back surface (taking a small sample after a certain period of time). In order to eliminate the disadvantage of the method of measuring wear using a microscope, one can also use automated measurement methods in the processing process, for example, machine vision methods [14, 15]. Using the methodology of processing the results, as well as using the proof that the wear value obeys the normal distribution law (Fig. 6, Table 4), find the areas under the distribution curve that correspond to excessively worn S_3 , correctly rejected S_2 , and inserts with a residual resource S_1 . The percentage of rejected excessively worn inserts

should be within 5%. With other percentages, it is necessary to analyze the trend. If production is functioning correctly, then S_2 should be maximum, S_1 should be minimum. In addition, a check is mandatory when it is necessary to assess the efficiency and qualifications of new engineering workers.

Of course, our technique should be more adequately applied to multi-blade machining and will work less effectively under single-blade conditions, such as turning. When turning, only one insert works at a time and known tool rejection systems (for example, by cutting forces, power or acoustic method) will show the need for replacement. The devised assessment methodology will only show if, for various reasons, the sensors that measure the signals have failed.

We shall evaluate the efficiency of the system by the percentage of inserts that are determined by the system as suitable for further use because this is an "unfinished" resource. Having determined the economic losses from insert rejection by formula (12), this amount must be added to the cost of production.

Thus, unlike the analytical, sensor, and intellectual methods considered in the literature review, which are aimed at predicting or online diagnostics of wear of a single tool, the proposed methodology solves another, previously insufficiently formalized problem, namely, a quantitative assessment of the efficiency of the existing system for rejecting carbide inserts under actual production conditions. This is achieved by classifying inserts by the degree of wear based on the area S_1 , S_2 and S_3 under the distribution curve and further assessing economic losses.

The proposed method has been devised mainly for managers at enterprises and structural units, for a simplified assessment of the efficiency of the existing system. It does not take into account the causes of wear and factors affecting it. This methodology produces a fairly reliable statement about the presence or absence of problems.

Our study in the future may be advanced through the possibility of using alternative probabilistic models of wear in cases of deviation from the normal distribution law, by integrating the proposed methodology with data from operational monitoring of the cutting process. It is also promising to use automated means of measuring wear and expand the methodology to other types of tools and production conditions, taking into account economic indicators.

7. Conclusions

1. Based on the statistical processing of results regarding the dimensional wear of carbide inserts after checking and screening out anomalous values, the homogeneity of the experimental samples was established by the Student's t -test with a probability of over 92% and Fisher's test, which allowed us to combine them into one set, for which the average value is $\bar{h} = 0.08145$ mm, the dispersion of scattering $D(h) = 0.00135$ mm², and the mean square deviation $\sigma(h) = 0.0375$ mm.

2. According to the Pearson criterion, it was proved that the value of dimensional radial wear obeys the normal distribution law. The equation of the density function of the distribution of radial wear of inserts was constructed.

3. With an allowable wear value of 1/3–1/4 of the size tolerance, based on the obtained dependences, it was found that 50.91% of the inserts could still be used (with different resources), 1.17% of the inserts were excessively worn (which

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