Вісник Тернопільського національного технічного університету
Scientific Journal of the Ternopil National Technical University
2018, № 1 (89)
ISSN 2522-4433. Web: ***visnyk.tntu.edu.ua***

MANUFACTURING ENGINEERING AND AUTOMATED PROCESSES

МАШИНОБУДУВАННЯ, АВТОМАТИЗАЦІЯ ВИРОБНИЦТВА ТА ПРОЦЕСИ МЕХАНІЧНОЇ ОБРОБКИ

UDC 621.834

THEORETICAL-PROBABILISTIC MODEL FOR DEFINING THE GEAR GRINDING STOCK ALLOWANCE

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Summary*. According to the stock allowance measurement results the theoretical-probabilistic model for determining the grinding stock allowance is determined. The model includes constant and variable components. The variable component of the stock allowance consists of the systematic periodic and random a periodic components. Methods for determining the gear grinding maximum stock allowance around the periphery of the gear depends on the number of measurements of the stock allowance. The stochastic and deterministic-stochastic stock allowance models for determination of the stock allowance maximum value on the basis of the results of its selective discrete measurements on a CNC machine are developed.*

Key words*: stock allowance, theoretical-probabilistic model, stock allowance constant and variable components, stock allowance systematic and random components, maximum stock allowance value, stochastic model, the deterministic-stochastic model.*

Received 26.12.2017

Statement of the problem. One of the input parameters of the technological grinding system is the actual value of the stock allowance for processing, particularly the maximum stock allowance value. This value is subdivided into the stages of the grinding and working strokes. The actual value of the maximum stock allowance for gear grinding can be determined using the built-in CNC measuring system on the machine adjustment stage. Measurement stock allowance on the periphery of gear makes it possible to take into account the individual characteristics of gear during gear grinding but it is followed by the increase operation component time. Therefore, it is necessary to reduce the time of the stock allowance measurement based on the principle of sampled equidistant measurements. But if the number of stock allowance measurements on the gear periphery is decreased, the uncertainty, for example, of the maximum stock allowance on gear grinding is increase resulting in the removal of the grinding wheel from the work piece. The value of the indicated wheel removal should be greater than the actual maximum stock allowance on gear grinding defined by the maximum number of allowance measurements to avoid the grinding wheel penetration into the work piece. To define the calculating maximum stock allowance by the limited number of its measurements, it is necessary to develop appropriate allowance models.

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Analysis of available investigation results. Stock allowances on the gear grinding operation of cylindrical gear are usually specified on reference tables and set perpendicular to the lateral tooth surface on the one or both of its sides [1, 2, 3]. The disadvantage of the tabular method of allowance assigning is that it does not take into account the individual characteristics of each gear wheel.

The calculation-analytical method for calculating the determination of minimum stock allowance during gear grinding taking into account the data of the theoretical analysis carried out in paper [5] is offered in paper [4]. The data of the stock allowance comparative analysis defined for the same conditions by experimental-statistical and calculation-analytical methods [6], according to which the first method gives an overestimated stock allowance in comparison with the second one are known.

The disadvantage of the given approach for determining the stock allowance on gear grinding is the lack of consideration of the individual stock allowance component on the gear periphery. Besides, in the calculation formula for the minimum stock allowance, there is no defective layer component, which is always present in the heat-treated gear, for example, in the form of the decarburized material layer [7]. There is no stock allowance separation into deterministic and random components.

Analysis of the methods of determining the stock allowance on the gear grinding proved that these methods are based on the known concepts of mechanical engineering technology (tabular and calculation - analytical) and take into account the gear features statistically. Built-in measuring systems on CNC machines make it possible to take into account the distribution on the gear wheel periphery for each work piece individually. But now there is no analysis of the structure of stock allowance on the gear grinding and techniques developed for a limited number of stock allowance measurements providing determination of the maximum calculating stock allowance on the basis of the defined structure.

The objective of the paper is to develop the theoretical concept of determining the stock allowance of the gear grinding according to the results of its discrete measurement and modelling on the basis of the theoretical-probabilistic approach. To develop methods for determining the maximum stock allowance for gear grinding on the basis of stochastic (with the number of measurements less than four) and deterministic-stochastic (with the number of measurements more than eight) models.

Statement of the problem. In the given paper the maximum stock allowance for gear grinding is determined by models based on its single measurement in the chosen gear tooth spaces along gear periphery. In this case stochastic and deterministic-stochastic models for various number of stock allowance measurements are developed.

The theory of determining the stock allowance on machining is one of the main sections in mechanical engineering technology and is connected with the general problem of technological processes modelling [6]. It is determined that the allowance for gear grinding contains z_0 constant and variable Δz components [8], each of which contains systematic and random components, for example, the variable component contains systematic Δz_{syst} and random Δz_{rand} components, that is,

$$\Delta z = \Delta z_{syst} + \Delta z_{rand} . \quad (1)$$

It is known that the systematic component of the stock allowance for machine parts of the prismatic form (flat surfaces) corresponds to the error of the installation (base) when measurement of the latter one on the machine is possible it is possible, otherwise it is considered as random. For "rotation body"-type parts (cylindrical surfaces), this component becomes periodic relatively to the diameter. For example, for gear pitch circle with eccentricity e relatively to the rotation axis of the grinding machine faceplate deviations Δy of diametric size occur, moreover $\Delta y = e \sin \varphi$ (φ – is the central angle of the pitch circle in the range 0 ... 2π). This results in to deviations (along the normal to the surface) of the lateral surfaces of the gear tooth spaces [9]

$$\Delta z_{syst} = \pm e\, sin\left(\varphi \pm \alpha\right), \qquad (2)$$

where α is the gear pressure angle.

In formula (2), different signs correspond to different sides of the gear tooth spaces. Thus, if it is possible to measure the stock allowance on the machine tool the error of gear setting resulting in eccentricity e, is the reason of the systematic periodic stock allowance component.

Factory practice shows that the number of the stock allowance measurements on gear periphery changes from the minimum (2-3 dimensions) to $N_{\max} = z$, where z – the number of teeth of gear. With a minimum number of measurements, there is a large proportion of the random component in the allowance size, since the amount of information received is not sufficient to allocate the systematic component. With a maximum number of measurements, the random component of the stock allowance is in a superposition with the systematic component and, first of all, with a systematic sinusoidal component, which is caused by the vector sum of the kinematic and geometric eccentricities [10]. Thus, in accordance with the adopted approach, the random stock allowance component is always present, but its specific gravity decreases as the number of measurements increases and within the limit (where $N \rightarrow N_{\max}$) this component tends to the measurement error (tenths of micrometers).

In accordance with the theoretical-probabilistic approach, we consider the variable component of the allowance Δz, assuming the presence of a systematic (periodic) Δz_{syst} and random (a periodic) Δz_{rand} component in it. Thus, the structural formula for the stock allowance $z(n)$ determination for the gear grinding for both profile sides of the tooth spaces has the form [11]

$$z(n) = z_0 + \Delta z(n) = z_0 + \Delta z_{syst}(n) + \Delta z_{rand}(n)\,, \qquad (3)$$

where n is current number of the gear tooth spaces, $1 \le n \le N_{\max}$.

To interpret the structural formula (1), let us consider the example. The distribution of the stock allowance on the left $z^L(n)$ and right $z^R(n)$ sides of the gear tooth spaces (code of the work piece DTMV.478.BE.40.005) has a sinusoidal nature of the change in the measuring circle of the gear (Fig. 1). The instantaneous values of these stock allowances are the sum of the constant (z_0^L or z_0^R in Fig. 1) and the variable ($z^L(n)$ or $z^R(n)$ in Fig. 1) of the components of this stock allowance. Moreover, the instantaneous value of the component of the stock allowance component in formula (3) can be positive and negative. In the first case, the instantaneous value of the corresponding stock allowance (on the right or left side of the hole) is greater than its constant component, in the second - less. So,

$$z^L(n) = z_0^L + \Delta z^L(n) = z_0^L + \left[\Delta z_\beta^L(n) + \Delta z_\gamma^L(n) \right], \tag{4}$$

$$z^R(n) = z_0^R + \Delta z^R(n) = z_0^R + \left[\Delta z_\beta^R(n) + \Delta z_\gamma^R(n) \right], \tag{5}$$

where $\Delta z_\beta^L(n)$ and $\Delta z_\gamma^L(n)$ are the systematic and random components of the variable component of the left-hand stock allowance, mm; $\Delta z_\beta^R(n)$ and $\Delta z_\gamma^R(n)$ are the systematic and random components of the variable component of the right-hand stock allowance, mm.

In equations (4) and (5), the systematic component of the variable component of the stock allowance can be replaced by the first harmonic of the corresponding Fourier series, i.e.,

$$\Delta z_\beta^L(n) = A_1^L \cos(\omega_1 t) + B_1^L \sin(\omega_1 t), \quad \Delta z_\beta^R(n) = A_1^R \cos(\omega_1 t) + B_1^R \sin(\omega_1 t),$$

where A_1^L, B_1^L, A_1^R, B_1^R are Fourier coefficients; $\omega_1 t$ is observation interval at the central angle, $0 \le \omega_1 t \le 2\pi$.

The obtained equations do not depend on the position of the gear initial tooth space where they perform the initial profile centering of the grinding wheel. When the accepted method the stock allowances aligning, for example, aligning of the minimum stock allowances is implemented, the constant components of stock allowances z_0^L and z_0^R z_0^L are changed in dependences (4) and (5).

Hence, these dependences while aligning the stock allowances by one of the known methods are moved along the axis of the ordinate in opposite directions, without changing its form. For example, when before the stock allowances $z_{\min}^L < z_{\min}^R$ are aligned then, after aligning the minimum stock allowance $z^L(n)$ dependence moves upward by the value $0,5(z_{\min}^R - z_{\min}^L)$, and the dependence $z^R(n)$ moves down on the same value.

The result of the minimum stock allowances aligning is the performance of the condition $z_{\min}^L = z_{\min}^R$. In this case

$$z_0 = 0,5(z_0^L + z_0^R) = \text{const}, \tag{6}$$

where z_0 is the average stock allowance value in all gear tooth spaces (mutual average).

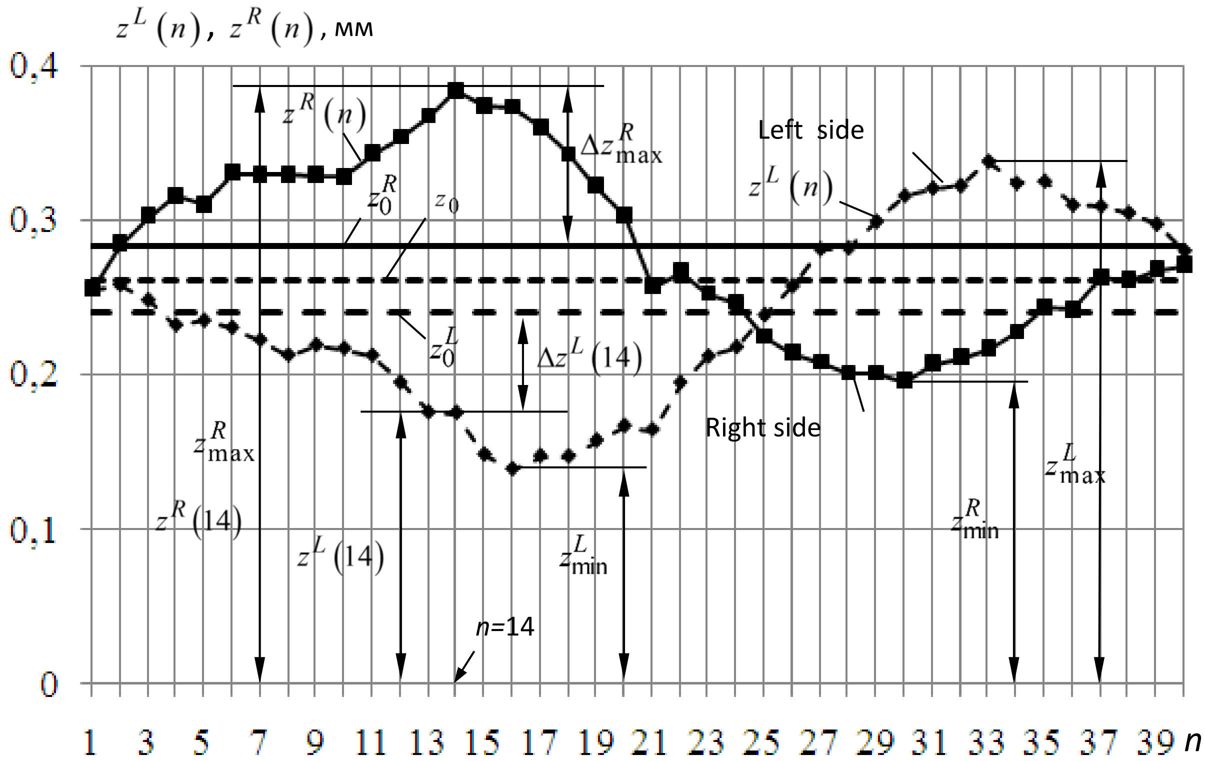

Figure 1. Distribution of stock allowance on the right and left sides of the gear spaces before aligning the minimum values of the stock allowance

Here for each N from the interval $1 \le N \le N_{max}$

$$z_0^L = \frac{1}{N} \sum_{n=1}^{N} z^L(n) \, , \tag{7}$$

$$z_0^R = \frac{1}{N} \sum_{n=1}^{N} z^R(n) \, , \tag{8}$$

$$z_0 = \frac{z_0^L + z_0^R}{2} \, , \tag{9}$$

$$z_0 = \frac{1}{N} \left(\sum_{n=1}^{N} z^L(n) + \sum_{n=1}^{N} z^R(n) \right) . \tag{10}$$

The stock allowance structure determines the structure of the stock allowance model. On the basis of the carried out researches it was established that with the small number of stock allowance measurements ($N \le 4$) the amplitude and the phase of systematic component occur with significant errors. At $N \ge$ 8, it is possible to separate the systematic component, for example, by the method of the least squares.

With the number of measurements $N \le 4$, the determination of the maximum stock allowance for gear grinding is carried out on the basis of a stochastic model due to the difference in one-sided stock allowances (accumulated circular pitch).

The maximum stock allowance is determined by the formula

$$z_{\max} = z_0 + \Delta z_{rand}, \quad (11)$$

where $\Delta z_{rand} = \varepsilon$, $\varepsilon = t_\gamma S_{\bar{x}}$, t_γ is the confidence coefficient; $S_{\bar{x}} = \frac{s}{\sqrt{N}}$ is the result mean square deviation, mm; $s = \frac{1}{\sqrt{N-1}} \sqrt{\sum_{j=0}^{N-1} \left(\Delta P(n_j) - \Delta \bar{P}\right)^2}$ – is the sampling mean square deviation (sample standard), mm; j is the variable uniformly located around the gear roundness; $0 \le j \le N-1$; $n_j = 1 + \frac{z}{N} j$; $0 \le n_j \le N_{\max}$; $\Delta P(n_j) = z^L(n_j) - z^R(n_j)$, $\Delta \bar{P} = \frac{1}{N} \sum_{j=0}^{N-1} \Delta P(n_j)$ is the deviation of the circular pitch and the mean value of the circular pitch deviation, relatively.

In the case of measurements number $N \ge 8$ the determination of the maximum stock allowance for gear grinding is carried out on the basis of a deterministic-stochastic model in two versions of its application: due to the difference of one-sided stock allowances; or due to one-sided stock allowance.

The maximum stock allowance, for example, defined by means of one-sided stock allowances difference, is determined by the formula

$$z_{\max} = z_0 + \Delta z_{syst} + \Delta z_{rand}, \quad (12)$$

where $\Delta z_{syst} = A/2 + c_0$ is the systematic component equal to the sum of half the amplitude A of the sinusoid recovered by the method of the least squares on discrete values of the circumferential pitch and the constant component c_0; $\Delta z_{rand} = \varepsilon$ for the random component of the circumferential pitch $\Delta P_\gamma(n_j)$ deflection. Moreover $s = \frac{1}{\sqrt{N-1}} \sqrt{\sum_{j=0}^{N-1} \left(\Delta P_\gamma(n_j) - \Delta \bar{P}\right)^2}$, $\Delta \bar{P} = \frac{1}{N} \sum_{j=0}^{N-1} \Delta P_\gamma(n_j)$. The amplitude of the circumferential pitch deflection is reviewed upwards or downwards from the level of the constant component c_0.

The workpiece gear DTMV 478BE 40.005 is made of steel 12X2H4A, which underwent cementation at a depth of h = 0,7...1,2 mm and hardening to HRC 58-60. Parameters of the gear: the number of teeth z = 40; the module m =3,75; the pitch diameter d =150 mm; the top diameter d_a =153,75 mm; the base diameter d_b =140,954 mm; the root diameter d_f =139,875 mm; the face width B=24 mm; the coefficient of initial contour displacement

x = – 0,3; the pressure angle α = 20°; the helix angle β=0. The Gear Quality Grade is 7-D. The roughness of the gear surface is Ra 3,2 μm.

The procedure for determining the maximum stock allowance is considered for gear DTMV 478BE 40.005 and contains the following steps.

1. After centring in the initial gear tooth space, the measurements of the stock allowance on the left (Fig. 2) and the right (Fig. 3) lateral sides of the wheel falls are carried out in limited number of times, for example, N = 8, i.e. j =8.

j	0	1	2	3	4	5	6	7
n_j	1	6	11	16	21	26	31	36

The minimum values of the stock allowance at centering in the initial tooth space are in the 16th tooth space (left side) and in the 31st tooth space (right side). At the same time $z_{\min}^{L}(16)$ =0,1393 mm (Fig. 2); $z_{\min}^{R}(31)$ =0,2074 mm (Fig. 3).

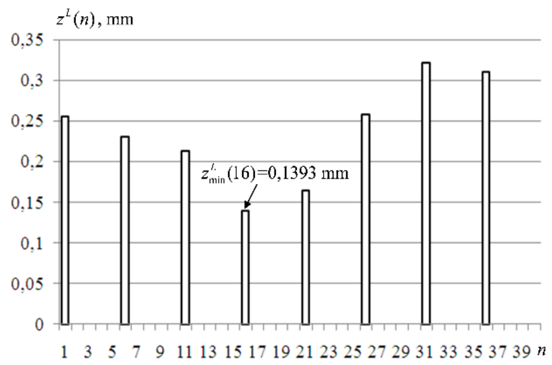

Figure 2. Distribution of the left stock before minimum values stock aligning

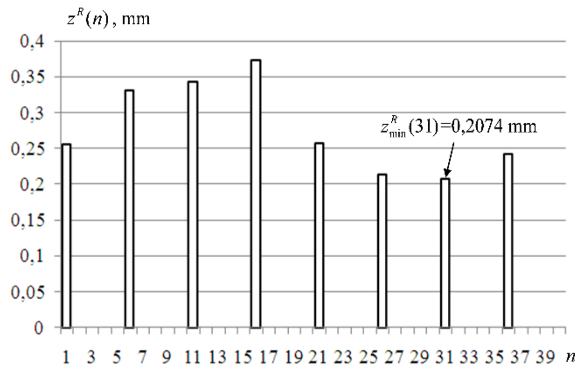

Figure 3. Distribution of the right stock before minimum values stock aligning

2. The minimum values of allowances are aligned on the lateral sides of the gear tooth spaces (Fig. 4, Fig. 5), i.e. $z_{\min}^{L} = z_{\min}^{R}$. In this case, after aligning the minimum values of stock allowances $z_{\min}^{L}(16) = z_{\min}^{R}(31)$ =0,1733 mm.

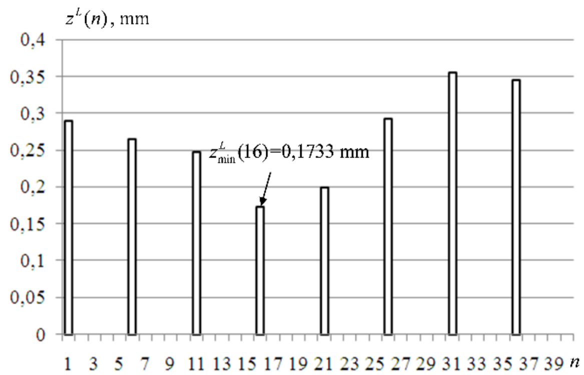

Figure 4. Distribution of the left stock allowance after aligning of the stock allowance minimum values

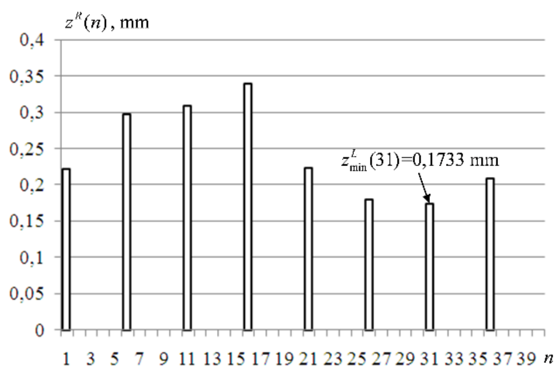

Figure 5. Distribution of the right stock allowance after aligning of the stock allowance minimum values

3. The average stock allowance on the left z_0^L and right z_0^R sides is determined after aligning of the minimum stock allowance values by formulas (7) and (8).

Here z_0^L =0,270663 mm; z_0^R =0,243975 mm.

4. The mean stock allowance is determined by the formula (9) from the gear defined at the selected number of *N:* z_0 =0,257319 mm.

5. The change of the circular pitch $\Delta P(n_j)$ deviation is determined from the gear measuring circle at different number of measurements (Fig.6). Since the stock allowance was measured in 1, 6, 11, 16, 21, 26, 31 and 36 tooth spaces, eight values of the circular pitch $\Delta P(n_j)$ deviation are defined at

n_j	1	6	11	16
$\Delta P(n_j)$, mm	0,0681	-0,0318	-0,0624	-0,166
n_j	21	26	31	36
$\Delta P(n_j)$, mm	-0,0244	0,1121	0,1819	0,1121

6. The systematic component of maximum stock allowance Δz_{syst} is determined.

In this case, in order to obtain the sinusoidal regression equation in the MathCAD program, it is necessary to set the values of the circular pitch (8 + 1) in order to obtain the equation in the period 2π. That is, additionally we set $\Delta P(41) = \Delta P(1)$ =0,0681 mm.

At *N*=8 the equation of the sinusoid, restored by the method of the least squares, is as follows $\Delta P(\Theta) = -0{,}146\sin(\Theta - 6{,}704) + 0{,}027$ (Fig. 6). The amplitude is A =0,146 mm. Thus, the systematic component of the stock allowance variable component is $\Delta z_{syst} = A/2 + c_0$=0,073+0,027=0,1 мм.

7. The random component of the deviation of the circular pitch $\Delta P_\gamma(n_j)$ is determined (Fig. 7). In this regard we subtract the sinusoidal component $\Delta P_\beta(n_j)$ from the discrete points of the circular pitch $\Delta P(n_j)$.

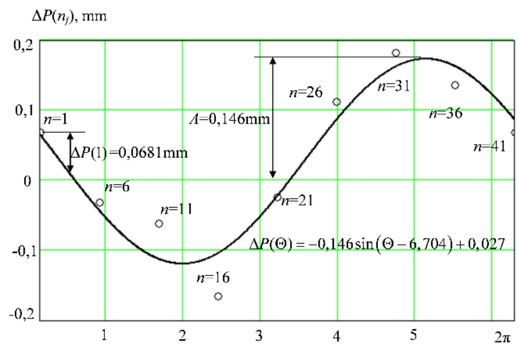

Figure 6. The equation of regression $\Delta P(\Theta)$ and circular pitch deviation $\Delta P(n_j)$ for N = 8

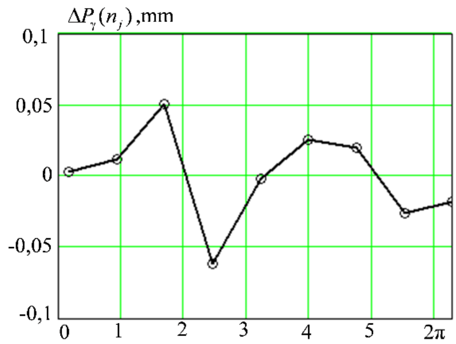

Figure 7. Random component of the pitch $\Delta P_\gamma(n_j)$

The one-sided confidential interval $\varepsilon = \Delta z_{rand}$ for the random component of the deviation of the circular pitch $\Delta P_{\gamma}(n_j)$ is determined.

The mean value of the random component is $\Delta \overline{P}$ =1,111·10^{-5} mm.

The sampling mean square deviation at N=8 S=0,035 mm.

The mean-square deviation of the result is $S_{\overline{x}} = \frac{s}{\sqrt{N}} = \frac{0,035}{\sqrt{8}} = 0,0123$ mm.

Then the one-sided confidential interval is $\Delta z_{rand} = \varepsilon = t_{\gamma}\, S_{\overline{x}} = 2,3646 \cdot 0,0123 = 0,02908$ mm.

8. The maximum allowance for gear grinding is determined according to the formula (12). Thus, $z_{\max}$ =0,257319+0,073+0,027+0,02908=0,3865 mm.

To ensure the reliable supply of maximum stock allowance the coefficient t_{γ} can be increased by increasing the confidential probability, for example, instead of 95% to take 99%.

Then $\varepsilon = t_{\gamma}\, S_{\overline{x}} = 3,5 \cdot 0,0123 = 0,04305$ mm. The maximum stock allowance here is

$z_{\max}$ =0,257319+0,073+0,027+0,04305=0,4004 mm.

Similarly, the maximum stock allowance are determined for N=10 і N =20. For N=10 $z_{\max}$ =0,379 mm; for N=20 $z_{\max}$ =0,3673 mm. The results of the maximum stock allowance calculations are tabulated in Table 1.

Table 1

Maximum stock allowance for different N for a deterministic-stochastic model

N	8	10	20
z_0, mm	0,2573	0,2587	0,2614
Δz_{syst}, mm	0,073	0,0733	0,0734
Δz_{rand}, mm	0,04305	0,033	0,0195
c_0, mm	0,027	0,01348	0,01299
$z_{\max}$, mm	0,4004	0,379	0,3673

Примітка: 1. $z_{\max}$ =0,3669 mm when N =40 (the maximum number of measurements); 2. To determine the $\Delta z_{rand} = t_{\gamma}\, S_{\overline{x}}$ the value t_{γ} is taken under 99 %

Analysis of the numerical results. According to the deterministic-stochastic model for different values N (8, 10, 20) the calculated maximum stock allowance is closer to the reference value (N = 40) as the number of measurements is larger.

Conclusions. The structure of the stock allowance for the gear grinding containing the constant and variable components is determined. Moreover the latter contains the systematic and random component. The elements of the deterministic and stochastic models of the stock allowance for their following use in the methods of the determination of the maximum stock allowance for gear grinding are developed. The area of use of the stock allowance models is defined: stochastic ($N \leq 4$) and deterministic-stochastic ($N \geq 8$). The developed stock allowance models make it possible to define the calculated maximum stock allowance for the gear grinding by its single measurements.

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УДК 621.834

ТЕОРЕТИКО-ЙМОВІРНІСНА МОДЕЛЬ ДЛЯ ВИЗНАЧЕННЯ ПРИПУСКУ НА ЗУБОШЛІФУВАННЯ

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Резюме. *За результатами вимірювання припуску встановлено теоретико-імовірнісну модель для визначення припуску на зубошліфування, відповідно до якої припуск на зубошліфування містить постійну і змінну складові. Розглянуто змінну складову припуску, припускаючи наявність у ній систематичної періодичної й випадкової аперіодичної компонент. Розроблено методи визначення максимального припуску на зубошліфування по периферії зубчастого колеса залежно від числа вимірювань припуску. Розроблено стохастичну і детерміновано-стохастичну моделі припуску для визначення максимального припуску за результатами його вибіркових дискретних вимірів на верстаті з ЧПК.*

Ключові слова: *припуск, теоретико-ймовірнісна модель, постійна і змінна складові припуску, систематична і випадкова компоненти припуску, максимальний припуск на зубошліфування, стохастична модель, детерміновано-стохастична модель.*

Отримано 26.12.2017