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THE EFFECT OF CUTTING TOOL WEAR ON THE RATE OF CORROSION WEAR OF A MACHINED MATERIAL

WPŁYW ZUŻYCIA NARZĘDZIA SKRAWAJĄCEGO NA INTENSYWNOŚĆ ZUŻYCIA KOROZYJNEGO WARSTWY WIERZCHNIEJ MATERIAŁU OBRABIANEGO

Key words: cutting, tool wear, corrosion wear, surface layer, surface roughness, cold hardening.

Abstract: A possible variant for calculated estimation of the degree of the impact of the cutting tool wear on the value of the part's surface layer wear obtained during processing with the edge tool, due to atmospheric corrosion, is presented. The feature is the evaluation of the wear rate and its numerical value depending on the tool wear, roughness parameters of the work piece surface, and the degree of cold hardening of the surface layer, as well as parameters of the technological machining conditions (cutting conditions, geometry of the tool cutting part, properties of the machined and the tool materials).

Słowa kluczowe: skrawanie, zużycie narzędzi, zużycie korozyjne, warstwa powierzchniowa, chropowatość powierzchni, utwardzanie na zimno.

Streszczenie: Zaproponowano sposób obliczeniowego oszacowania wpływu zużycia narzędzi skrawających na intensywność zużywania korozyjnego warstwy wierzchniej materiału obrabianego. Cechą charakterystyczną podejścia jest ocena stopnia zużycia korozyjnego w zależności od zużycia narzędzia, parametrów chropowatości powierzchni przedmiotu obrabianego i stopnia utwardzania warstwy wierzchniej na zimno, a także parametrów warunków obróbki technologicznej (parametrów skrawania, geometrii narzędzia skrawającego, właściwości obrabianego materiału i narzędzia).

INTRODUCTION

An important and responsible stage for predictive estimates of atmospheric corrosion is the theoretically substantiated choice of the main factors affecting corrosion. In some cases, in dry air at normal temperatures, the part material has sufficient resistance, which can be explained by the fact that the natural oxide film formed on the metal surface protects the material from further exposure to moisture and oxygen. In humid air, in fresh and especially in seawater, the part material corrodes relatively quickly.

The development of theoretical and experimental simulation of atmospheric corrosion is essential for understanding its chemical and electrochemical mechanism. It is equally important for practical tasks, such as the development of scientific methods for predicting corrosion rates and evaluating long-term corrosion effects on materials in different regions of the world, and for obtaining cost estimates of the damage caused by atmospheric corrosion. For example, aircraft gas turbine engines operating in Algeria, India, and St. Petersburg have a greater rejection of blades with corrosion than the blades from the engines operating in Kazakhstan, where there is less presence of corrosive impurities in the air.

The blades dominating rejection are those of the aircraft gas turbine engines operating in Algeria, India,

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St. Petersburg, and Vladivostok, where the blade surface layer material is more sensitive to corrosion due to the marine climate than those on the engines operating in Dagestan, Kazakhstan, and China (**Fig. 1**).

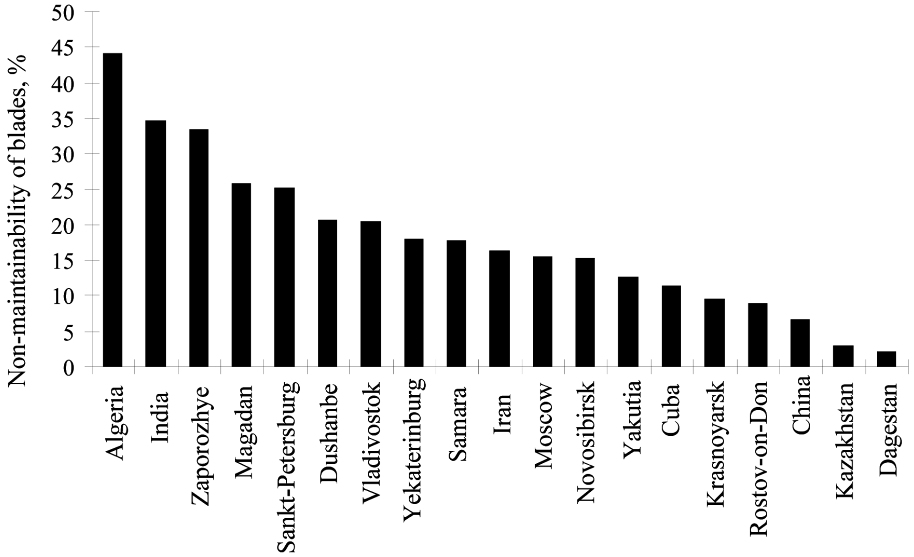

Fig. 1. Diagram on the non-maintainability of blades depending on the operating site
Rys. 1. Procentowy udział łopatek turbin wyłączonych z eksploatacji w zależności od miejsca użytkowania

According to the figures provided by statistical studies, the rate of atmospheric corrosion of aluminium blades is maximal in the industrial atmosphere; it is very high in the northern sea airports, and it is minimal in the dry areas. The main adverse factor in the northern sea airports is the long duration of surface dampening. The corrosion rate in unheated premises is higher than in the open air.

The performance characteristics of the part, including the corrosion resistance of its surfaces, are largely determined by the processing conditions, which is a complex characteristic that can be the wear of the cutting tool during processing. It can be set by the height of worn area of the cutting part of the tool on clearance face δ or by value $_{in}$, indicating the bit dimensional wear. The values characterizing the bit wear are interrelated by dependence $\Delta_{in} = \delta \cdot \mathrm{tg}\alpha$, where is the tool back clearance.

WORK OBJECTIVE

The work piece material surface layer corrosion rate is to a significant extent determined by the quality parameters of its surface layer, which hinge on the operating conditions of surface cutting, conditioning the cutting tool wear. In this regard, the aim is to determine theoretical dependencies in terms of the relationships between the rate and value of corrosion wear of the work piece surface and operating conditions of their cutting (cutting mode, geometry of the cutting tool, etc.), characterizing the cutting tool wear.

RESEARCH METHOD

It is advisable to study the influence of operating conditions of cutting (cutting modes and geometry parameters of the tool cutting part, as well as the work piece material and the tool cutting part) on wear by comparing the corrosion rate of the sample material with the corrosion rate of the reference material machined under the accepted operating conditions of cutting. In this case, the reference material should be subjected to annealing to remove residual stresses and cold hardening in the surface layer of the material and should be handled with sandpaper to remove the metal oxide layers from the surface to be compared, and polished with a felt wheel with GOI polishing paste. In accordance with studies **[L. 1]**, the reference material should have the following quality parameters of the material surface layer: degree of cold hardening, $U_H = 1.0$; height of irregularities, $Rz = 0.15$ μm; and a relative profile reference length of the surface profile along the mid-line, $t_m = 50$ %.

A comparison of the corrosion rate of the reference material and the corrosion rate of the reference material after machining allows determining the degree of the influence of operating conditions on the corrosion resistance of the material of the machined surface:

$$\frac{V_K}{V_{K0}} = KC\,,$$

where V_K is the corrosion rate of the material on the machined surface; is the corrosion rate of the material of the reference surface; and, KC is the complex parameter of the corrosion rate.

THE BODY OF RESEARCH

In accordance with studies **[L. 1]**, the complex parameter of the corrosion wear rate KC is determined by the following formula:

$$KC = b_0 U_H^{b_1}\left[\frac{28\cdot 10^6 R_V}{(100-t_m)^2 S_m{}^2}\right]^n,$$

where U_H – is the cold hardening degree of the work piece material surface layer after machining, %; R_V – is the maximum profile valley depth, μm; S_m – is the pitch of irregularities on the part surface along the mid-line, μm; t_m – is the relative profile reference length of the surface profile along the mid-line, %; b_0 and b_1 are the coefficients, depending on the material grade and state, e.g., for non-thermostrengthened steel $b_0 = 1.0$ and $b_1 = 5.2$; for thermostrengthened low-alloy steel $b_0 = 0.73$ and $b_1 = 5.72$; for thermostrengthened medium-alloy steel $b_0 = 0.74$ and $b_1 = 5.57$; and, n is the corrosion type-oriented coefficient ($n = 0.66$ for corrosion in fluids; and, $n = 0.5$ for atmospheric corrosion).

According to **[L. 3]**, the t_m value is determined by the following formula:

$$t_m = 100 - \sqrt{\frac{2\cdot 10^4 Rz}{S_m}} \tag{1}$$

and value $R_V = 0{,}55\ Rz$, where Rz is the average value of the height of irregularities on the work piece surface, μm.

Taking into account values t_m and R_V, the formula to determine calculated value KC after mathematical transformations to define KC will take the following form:

$$KC = 770\frac{b_0 U_H^{b_1}}{S_m} \tag{2}$$

In accordance with the author's research presented in **[L. 2]**, the value of the pitch of irregularities on the work piece surface along the mid-line can be determined by the following formulas:

$$\begin{gathered}
S_m = 2\sqrt{Rz(2r-Rz)}\,,\ \text{mm} \qquad \text{at} \qquad S \le 2r\sin\varphi_1 \\
S_m = 2r\sin\left[\phi_1 - \operatorname{arctg}\frac{r-(1-\cos\phi_1)-0.5Rz}{r\sin\phi_1}\right] + Rz\operatorname{ctg}\phi_1\,,\ \text{mm} \\
\text{at} \qquad 2r\sin\varphi_1 < S \le r\times\left[\frac{1-\cos(\phi+\phi_1)}{\sin\phi_1}\right] \\
S_m = \frac{2r(1-\cos\phi_1)}{\sin\phi_1} + 0.5Rz(\operatorname{ctg}\phi + 3\operatorname{ctg}\phi_1)\,,\ \text{mm} \\
\text{at} \qquad S > r\left[\frac{1-\cos(\phi+\phi_1)}{\sin\phi_1}\right],
\end{gathered} \tag{3}$$

where S – is the feed, mm; r – is the cutter tip radius in plan, mm; φ and φ_1 – are the major and auxiliary cutting edge angles in plan, deg.; and, Rz – is the height of irregularities on the work piece surface, mm.

At optimal cutting rates corresponding to the minimal wear of the cutting tool, the height of irregularities on the work piece surface is calculated by the following formula **[L. 2]**:

$$Rz = \frac{1}{8r}\left\{\frac{0.6625a_1^{0.125}c\rho\theta_0\left[4{,}3\sin^{0.115}\alpha \mathrm{v}_0^{0.57}a_1^{0.345}\lambda\left(\frac{t}{m}\right)^{0.3} + \lambda_P\beta\varepsilon a^{0.57}\rho_1^{0.075}\right]}{\left[\tau_P a^{-0.43}(\sin^{0.025}\alpha)\mathrm{v}_0\lambda t^{0.25}m^{0.74-n_0}\times c_0 b^{0.04}\rho_1^{n_0-0.1}(1-0.45\sin\gamma)\right]}\right\}^{\frac{2}{1-n_0}}\,,\ \text{m} \tag{4}$$

where – τ_p is the flow shear strength of the work piece material, Pa; a_1 is the cut cross section thickness, m; θ_0 – is the optimal temperature in the cutting area providing minimal cutting tool wear, °C; cρ – is the specific volumetric heat capacity of the work stock, Joule/(m^3 K); v_0 is the optimal cutting rate, m/s; λ and λ_p are the coefficients of the thermal expansion of the work piece material and the tool material, W/(m K); t – is the cutting depth, m; α and γ are the end and the face tool edge angles, deg.; β and ε are the cutting point angle and the cutter tip angle in the plan, deg.; a – is the temperature diffusivity of the work piece material, m^2/s; ρ_1 – is the tool tip corner radius, m; b – is the length of the contact between the tool tip and the work piece material, m; $m = a_1/S$ – is the coefficient depending on the cutting tool geometry parameters; S – is the feed, m; C_0 and n_0 are the coefficients dependent on the combination of properties of the work stock and the tool material, as well as on the relation between the tool tip corner radius and cut cross section thickness a_1; and, r – is the cutter tip radius in plan, m.

According to the study of the author, the degree of cold hardening of the work piece surface layer when edge tool cutting is determined by the following formula **[L. 2]**:

$$U_\text{H} = 1 + N = 1 + \frac{h_\text{H}}{125(\sigma_\text{D}/\sigma_\text{DB})^{0.8}} \tag{5}$$

where σ_D is the tensile strength of the work piece material, MPa; h_H is the cold hardening depth in the work piece material surface layer when edge tool cutting with wear of its cutting part defined by the following formula:

$$h_\text{H} = \frac{0,76 \cdot 10^{-6}\, \tau_P^{0.75} S^{0.6} t^{0.06} \rho_1^{0.17} \phi^{0.35} \cdot \delta^{0.36}}{\text{v}^{0.28} r^{3.5S^{1.7}} \alpha^{0.09} \gamma^{0.33}}, \text{ m} \tag{6}$$

and when machining with a cutter without its wear – according to the following formula:

$$h_\text{H} = \frac{2.36 \cdot 10^{-8}\, \tau_P^{0.75} S^{0.6} t^{0.06} \rho_1^{0.17} \cdot \phi^{0.35}}{\text{v}^{0.28} r^{3.5 \cdot S^{1.}} \alpha^{0.09} \gamma^{0.33}}, \text{ m} \tag{7}$$

where τ_p in Pa; S in mpr; t in m; ρ_1 in m; α, γ and φ – is the major cutting edge angle in plan, in deg.; r and ρ_1 in m; δ is the wear flat land height of the cutter along the end surface, m; σ_DB – is the tensile strength of the electric steel, MPa; and, v – is the cutting rate, m/s.

The above method applied to determine coefficient *KC* (the complex parameter of corrosion rate) allows studying the impact of both the parameters of the surface layer quality (parameters of roughness, the degree and depth of cold hardening of the surface layer) and operating conditions of surface machining (cutting mode and geometry parameters of the tool cutting part), as well as physical and mechanical properties of the work stock and the tool materials on corrosion resistance.

Assessment of the impact of corrosion on the quality of the surface layer is possible by determining the degree of change in the height of irregularities on the surface under study, due to the course of corrosion processes. According to the research of Fedonin O.N., the height of irregularities on the part surface after rusting can be defined by the following formula **[L. 3]**

$$Rz = Rz_\text{in} + \Delta Rz + \Delta\rho_w - \Delta\rho_m,$$

where Rz_in – is the initial value of the height of irregularities on the work piece surface; $\Delta Rz = \rho_w$ – is the roughness profile height increment due to corrosion, because corrosion primarily occurs in the irregularity profile valleys on the work piece surface; $\Delta\rho_w = V_\text{к}\,\tau$ – is the variation in the pitting corrosion in the irregularity profile valley; $\Delta\rho_m = V_\text{к}\,\tau\, K_\text{в}$ – is the variation in the rounded radius of the irregularity profile peaks; $V_\text{к}$ – is the part material corrosion rate under the present conditions; τ is the rusting time; and, $K_\text{в} = 1.28…2.0$ – is the coefficient taking into account the relation of corrosion rate of the peaks and valleys of the material.

Value ρ_w is defined according to the following formula **[L. 3]**:

$$\rho_w = \sqrt[3]{\frac{3V_\text{к}\,\tau\, S_m\, Rz}{4\sin\beta}},$$

where β is the irregularity profile grade angle; and, S_m is the average pitch of irregularity profile.

At optimal cutting rates corresponding to the minimal wear of the cutting tool, the height of irregularities on the work piece surface is calculated by the following formula **[L. 2]**:

$$Rz_\text{in} = \frac{1}{8r}\left\{\frac{0.6625 a_1^{0.125} c\rho\theta_0 \left[4.3(\sin^{0.115}\alpha)\text{v}_0^{0.57} a_1^{0.345} \lambda \left(\frac{t}{m}\right)^{0.3} + \lambda_P \beta\varepsilon a^{0.57} \rho_1^{0.075}\right]}{\left[\tau_P a^{-0.43}(\sin^{0.025}\alpha)\text{v}_0 \lambda t^{0.25} m^{0.74-n_0} \times c_0 b^{0.04} \rho_1^{n_0-0.1}(1-0.45\sin\gamma)\right]}\right\}^{\frac{2}{1-n_0}}, \text{ m} \tag{8}$$

Therefore, the height of irregularities on the work piece surface due to corrosion processes is determined by the following formula:

$$Rz = Rz_{\text{in}} + \sqrt[3]{\frac{3V_{\text{к}}\,\tau\, S_m\, Rz}{4\sin\beta}} + V_{\text{к}}\tau(1 - K_{\text{в}}) \qquad (9)$$

EXAMPLE OF CALCULATING THE CORROSION RATE PARAMETER VALUE AND THE HEIGHT OF IRREGULARITIES ON THE TEST SURFACE DUE TO CORROSION WEAR

The initial cutting conditions are as follows:

- Work piece material – steel 40;
- Tool cutting part material – T15K6;
- Cutting conditions: *S* = 0.1 mm/pr, v = 3 m/s, *t* = 0.5 mm;
- Tool cutting part geometry parameters; α = 15 deg.; γ = 5 deg., φ = 45 deg., φ_1 = 15 deg., *r* = 1 mm; ρ_1 = 30 µm; δ_1 = 0.2 mm;
- $\frac{\sigma_D}{\sigma_{DB}} = 1.7$;
- Rusting time – 1 year;
- $v_{\text{к}} = 0.019$ (according to Fedonin O. N.) **[L. 1]**.

The calculation sequence is as follows:

1. The value of the cold hardening degree of the work piece surface according to Formula (5) when chiselling with flank land δ = 0.2 mm is *N* – 1.40.
2. The irregularity height on the work piece surface when chiselling with flank land = 0.2 mm is Rz_{in} = 2.9 µm.
3. The irregularity pitch on the reference surface calculated according to Formula (3) under condition of cutting with a tool with wear δ = 0.2 mm is S_m = 152 µm.
4. The parameter of corrosion wear rate calculated according to Formula (2) with tool flank land δ = 0.2 mm is *KC* = 36.9.
5. The surface finish on the work piece surface due to corrosion processes when chiselling with flank land δ = 0.2 mm will amount to *Rz* = 4.88 µm.

In accordance with the above example, calculations were made in terms of the height of irregularities on the work piece surface due to corrosion wear of the work piece surface when processing with a cutter with different values of wear indicators of the cutting tool (**Table 1**). Based on the results of the calculation, dependency graphs of *Rz* and *KC* values on the degree of wear of the cutting tool were constructed (**Figs. 2** and **3**). These values were used to obtain dependences for determining the indicators of surface corrosion wear taking into account the wear of the cutting tool.

The value of irregularities on the work piece surface due to the corrosion wear is as follows:

$$Rz = 8.896\ (\Delta_{\text{in}}/\text{tg}\alpha)^{0.27} \qquad (10)$$

where value Δ_{in}, in mm; and, α is the clearance angle, deg.

The corrosion wear rate parameter is as follows:

$$KC = 30.661\ (\Delta_{\text{in}}/\text{tg}\alpha)^{0.067} \qquad (11)$$

Table 1. Dependence of corrosion wear indicators on cutting tool wear degree when cutting

Tabela 1. Zależność wskaźników zużycia korozyjnego od stopnia zużycia narzędzi podczas skrawania

Cutting tool wear indicators		Initial height of irregularities on the work piece surface, Rz_{in}, µm	Cold hardening depth in the surface layer of the machined surface, µm	Cold hardening degree in the surface layer of the machined surface	Irregularity pitch on the machined surface, S_m, µm	Corrosion wear rate parameter, *KC*	Height of irregularities on the machined surface after corrosion wear, *Rz*, µm,
δ, mm	Δ_{in}, mm						
0.05	0.014	2.3	45.8	1.22	135	36.2	4.25
0.2	0.054	2.9	68.6	1.40	152	36.9	4.88
0.3	0.081	3.9	79.4	1.47	176	33.4	6.51
0.5	0.135	5.1	95.4	1.56	201	31.1	7.75
0.7	0.189	5.6	107.7	1.63	211	30.9	8.38

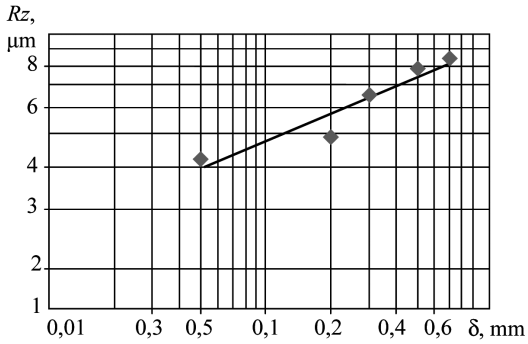

Fig. 2. Dependence of the height of irregularities on work piece surface *Rz* due to corrosion processes on cutting tool flank land δ

Rys. 2. Zależność wielkości parametru chropowatości obrabianego elementu *Rz* wynikającego z procesów korozji od zużycia powierzchni przyłożenia narzędzia skrawającego δ

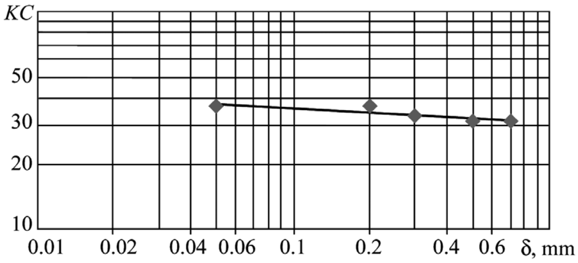

Fig. 3. Dependence of the corrosion wear rate parameter of work piece surface *KC* on cutting tool flank land δ

Rys. 3. Zależność wskaźnika zużycia korozyjnego obrabianego elementu *KC* od zużycia powierzchni przyłożenia narzędzia skrawającego δ

For specific groups of work piece materials, the numerical value of the wear of the cutting tool can be determined using the following formula **[L. 2]**

$$\Delta_{\mathrm{in}} = c_1 \frac{\pi d l}{S}\left(\frac{\sigma_{\mathrm{D}}}{\sigma_{\mathrm{DB}}}\right)^{x_{\mathrm{in}}} (\mathrm{DB})^{y_{\mathrm{in}}} E^{z_{\mathrm{in}}}, \text{ mm}$$

where d and l – are the diameter and the length of the machined areas of the work piece, mm; S – is the feed, mm/pr; σ_D and σ_{DB} – are the tensile strength of the work piece material and that of the electric steel, respectively, MPa; $D = \mathrm{v}a_1/a$ – is the dimensionless group of the cutting process, where v is the cutting rate, m/s; a_1 – is the cut cross-section thickness, m; and, a – is the temperature diffusivity of the work piece material, m^2/s; $B = \mathrm{tg}\beta_1$, where β_1 – is the inclination of the conditional shift plane, deg. **[L. 2]**, $E = \delta_1/a_1$ – is the dimensionless group of the cutting process, where δ_1 is the cutter bit corner radius, m; c_1, x_{in}, y_{in}, z_{in} – are the values presented in **Table 2**.

Table 2. Values of the coefficients in the formula for calculation Δ_{in}

Tabela 2. Wartości współczynników stosowanych przy obliczaniu Δ_{in}

Material group	Coefficients			
	c_1	x_{in}	y_{in}	z_{in}
Aluminium alloys	$1.79 \cdot 10^{-3}$	0	$3.14\sqrt{\frac{k\lambda_P}{\lambda}}$	2.03
Copper alloys	$1.34 \cdot 10^{-3}$	0	$3.80\sqrt{\frac{k\lambda_P}{\lambda}}$	2.63
Magnesium alloys	0.26	0	$2.71\sqrt{\frac{k\lambda_P}{\lambda}}$	2.26
Carbon alloy steels	$6.68 \cdot 10^{-8}$	0	$2.70\sqrt{\frac{k\lambda_P}{\lambda}}$	3.79
Stainless and heat-resistant steels	$1.38 \cdot 10^{-8}$	1.88	$1.10\sqrt{\frac{k\lambda_P}{\lambda}}$	1.66
Titanium alloys	$2.79 \cdot 10^{-11}$	3.49	$3.14\sqrt{\frac{k\lambda_P}{\lambda}}$	6.31
Nickel alloys	$2.05 \cdot 10^{-7}$	2.30	$0.92\sqrt{\frac{k\lambda_P}{\lambda}}$	1.70

Note to Table 2: λ are λ_0 are the thermal conductivity coefficients of the work piece and the tool materials; $k = 1$ for tungsten-cobalt hard alloys; $k = 1.5$ for high-speed tool alloys; and $k = 1.8$ for titan-tungsten-cobalt hard alloys.

CONCLUSIONS

When finishing, the permissible wear of the cutting tool is regulated. In this regard, Formulas (10) and (11) allow controlling the cutting process in order to provide specified performance characteristics of parts, in particular, indicators of the corrosion wear of the work piece surface.

It is possible to control the cutting process ensuring the required surface roughness during operation in order to obtain the permissible value of the change in the parameters of roughness caused by corrosion of the part surface layer material, which is essential during preproduction design and engineering.

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