Vjacheslav F. BEZJAZYCHNYI*, Marian SZCZEREK**

THE INFLUENCE OF SURFACE LAYER QUALITY ON THE PERFORMANCE CHARACTERISTICS OF MACHINE PARTS UNDER MACHINING

The paper highlights the classification of the quality parameters of the surface layer and their influence on the performance characteristics of machine parts, such as wear resistance, long-term and endurance strength, as well as the influence of quality parameters of the surface layer on the performance characteristics subject to the operating conditions (various temperatures and loads). The paper expounds the impact of machining conditions on the formation of surface layer quality indices and provides calculated dependences for the determination of surface layer quality parameters.

Key words: surface, roughness, residual stresses, degree and depth of cold working, performance characteristics, wear resistance, strength endurance, processing rates.

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Słowa kluczowe: powierzchnia, chropowatość, naprężenia własne, zgnoi, głębokość obróbki plastycznej na zimno, parametry eksploatacyjne, odporność na zużywanie, wytrzymałość, parametry obróbki.


INTRODUCTION

The improvement of the quality of engineering products can be achieved through the enhancement of the performance characteristics of machine parts, which depend to a great extent on the quality of the surface layer. Sometimes the latter often determines the part service life, rather than the characteristics of machining accuracy. This problem is particularly relevant in the aircraft industry, space technology, etc., where destruction of critical parts can lead to disaster.

Considering the mechanism of surface layer formation during machining and current knowledge of the solid-state physics and the plastic collapse theory, Professors A.M. Sulima and M.I. Evstigneev proposed the following classification of surface layer parameters, Table 1 [L. 1].

THE BODY OF RESEARCH

The influence of surface layer parameters on the performance characteristics of machine parts is sufficiently studied in terms of roughness, residual stresses, and cold working. However, in the literature, different opinions are encountered about the degree of the influence of roughness, residual stresses, the degree and depth of cold working on fatigue properties, and other performance characteristics of machine parts. There are recommendations that can be used in the production environment. Thus, according to the research of Professor A.M. Sulima, the endurance of high-temperature alloys at working temperatures and high frequency loading depends significantly on surface roughness. He found that the increase of surface roughness $R_z$ from 0.05 µm to 2.0 µm reduces fatigue.

* Solovyov Rybinsk State Aviation Technical University, Rybinsk, Russia.
** Institute for Sustainable Technologies – National Research Institute, ul. Pułaskiego 6/10, 26-600 Radom, Poland.
The decrease in the fatigue resistance of alloys after grinding, when surface microroughnesses are located perpendicularly to the axis of the sample, is 1.5 times more than when the microroughnesses are located along the axis of the specimen at the same values of roughness. Thus, not only the height of irregularities and their shape hold much significance, but also the location of irregularities in relation to the load applied to the part.

There is also no shared vision of the influence of cold working on cyclic strength. According to Professor Kudryavtsev I. V. and Professor Oding I. A., cold working results in an increase in the fatigue limit. Sulima A. M. et al. found that the influence of cold working in the surface layer on the endurance of heat-resistant alloys is dual:

- When the parts operate in relatively low temperatures and at relatively low resource of operation, cold working increases resistance of high-temperature alloys to fracture, which is associated with increasing resistance to separation as a result of structural changes under the influence of plastic deformation.
- With increase of operating temperature and service life, cold working facilitates the intensification of processes in terms of material structure change as a result of oxidation, burning-out and the evaporation of alloying agents, which can lead to embrittlement and a loss of heat resistance. There is a belief that, for parts made of heat-resistant steels and an alloy operating at high temperatures, the surface layer without cold working or with rather insignificant cold working is desirable, which should be established depending on the working temperature.

The influence of residual stresses on endurance is responsible for the fatigue failure mechanism, based on the formation and propagation of fatigue microcracks in the process of cycling loading. Here, the surface-active agents penetrating the microcracks favour their propagation wedging their walls in the course of deformation. Factors facilitating the formation of fatigue

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microcracks and assisting their further propagation will decrease the fatigue limit, and factors impeding crack formation and decelerating their propagation will favour endurance increase. To the factors impeding crack formations belong the residual compressive stresses in the surface layer including the contribution from the acting external stresses reduce cyclic tensile stresses. In contrast with the residual compressive stresses the tensile ones including contribution from the acting cyclic applied tensile stresses accelerate fatigue crack formation and reduce fatigue limit [L. 8]. It is difficult to estimate the degree of the influence of residual stresses on resistance to fatigue along with other quality parameters of the surface layer, because they change in terms of value during operation. However, it was found that the influence of residual stresses on fatigue resistance prevails for high-strength metals, and the influence of cold working predominates for low-strength metals.

The nature of the influence of residual stresses in the surface layer and the depth and degree of cold working on fatigue strength depends on the technology of part manufacture. In his research, Professor Kravchenko B.A. found that, during machining a ductile material tensile residual stresses occur on the machined surface, and during machining, brittle material the compressive ones form [L. 2]. Predeformation hardens the material reducing its plastic properties; therefore, when machining the material in hardened condition, the minor tensile residual stresses form, and at a certain depth, they transform into the compressive ones that should increase the endurance limit. In order to confirm this, a study was carried out on three sample batches made of normalized steel IXI8H9T. All samples were finish-turned (cutting rate \( v = 15 \text{ m/m} \); cutting depth \( t = 0.1 \text{ mm} \); feed \( S = 0.05 \text{ mm/rev.} \)), and then they were polished with abrasive paper. The first batch was produced from unstrained material. The samples of the second batch were deformed after manufacture with 20% elongation, and the samples of the third batch were made of bars being predeformed with elongation up to 20%. In the surface layer of the first batch, tensile residual stresses \( \sigma_{0\max} = 80 \text{ MPa} \) were formed. In the second case, the residual stresses reduced to \( \sigma_{0\max} = 80 \text{ MPa} \), and in the third case, the residual stresses made up \( \sigma_{0\max} = -300 \text{ MPa} \) (Fig. 1).

Tests showed that the samples made of predeformed bars with compressive stresses in their surface layer possess the maximum endurance limit. The observed increase of the endurance limit in the predeformed samples stems from the simultaneous action of compressive residual stresses and cold working.

To determine the effect of only cold working on the endurance limit by anodic dissolution, the surface layer of all samples with a thickness of 200 \( \mu \text{m} \) was removed, i.e. the residual stresses were virtually completely removed. Fatigue tests of these samples (after polishing) showed that, for unstrained samples, the endurance limit increases in comparison to the unpolished samples. The latter can be explained by the elimination of detrimental effect of tensile residual stresses. The same is observed for samples deformed after turning. The polished samples produced from tensile-predeformed bars demonstrated a decrease of endurance limit stemming from the elimination of the influence of useful compressive residual stresses.

Research on the influence of manufacturing technology on the endurance limit showed that cold-worked samples after turning have an endurance limit of \( \sigma_{-1} = 375 \text{ MPa} \), and that of the non-cold-worked ones makes up \( \sigma_{-1} = 355 \text{ MPa} \). The increase of endurance limit due to hardening makes up 5.7%. Under simultaneous influence of cold working and residual stresses, the similar comparison gives 18.2%, i.e. the change of endurance limit due to only residual stresses makes up 12.5%. Therefore, the proportion of the influence of residual stresses on the endurance limit is 69%, and that of cold working makes up 31%.

The study of Professor Matalin A. A. establishes that residual stresses, cold working, and surface roughness change fatigue strength by a ratio of \( 1.5 \times 1.25 \times 1.03 \). According to the research of Sulima A. M., the influence of surface roughness and the depth of cold working on resistance to fatigue is more considerable and, in some cases, cold working reduces endurance. However, it is known that hardening technology increases endurance limit. The apparent contradiction is explained by the fact that, when hardening, favourable residual stresses are induced which, through their positive effect, cover
the adverse impact of cold working. According to the research of Sulima A. M., the relative significance of each parameter of surface layer quality in the decrease of resistance to fatigue for the samples after grinding is as follows: surface roughness up to 50–70%, cold working of the surface layer 25–45%, and technological residual macrostresses up to 5–15%. Then fatigue strength of heat-resistant steels and alloys at working temperatures and high frequency loading depends substantially on surface roughness, depth, and the degree of cold working in the surface layer. Residual stresses relax under conditions of high temperatures and exert practically no influence on fatigue stress; however, under conditions of low temperatures, their influence is essential. Strain hardening of the surface layer after cutting reduces the fatigue strength of heat-resistant materials at elevated temperatures. If we consider the influence of cold working on long-term strength at elevated temperatures (700°C and above), it should be noted that cold working reduces long-term strength. The maximum strength is observed when polishing, and the minimal one is during the hardening machining.

For some materials, Professor Sulima A. M. determined the optimal values of the degree and the depth of cold working of surface layers for aircraft engine parts, and when they are exceeded, fatigue strength is reduced. The study of Professor Sulima A. M. also establishes that the most efficient technological option to machine parts made of heat-resistant steels and alloys providing the maximal fatigue endurance at working temperatures is as follows: electrochemical machining with subsequent vibrocontact polishing or strain hardening creating surface cold working of low depth and intensity. In accordance with the study of Kravchenko B. A., in this case, favourable residual stresses in the surface layer are also formed.

Machine part surface roughness exerts considerable influence on wear resistance. However, the surface with the minimal roughness does not always turn out to be the most wear resistant. This is because the very close rapprochement of two solid bodies results in a molecular interaction between surfaces and increases their cohesion increasing wear (Fig. 2) [L. 2]. At small values of roughness height on the surface, seizure occurs. At considerable values of roughness height on the surfaces, mechanical adhesion and cut occur.

It has been found that, in the process of wear after running in, the optimal equilibrium roughness is formed that does not depend on the initial roughness. Therefore, it is a good practice during machining to create surfaces where roughness will correspond to run-in friction surfaces under certain wear conditions. In the course of running-in surface roughness of samples A decreases, that of samples B increases, but samples C have constant roughness (Fig. 3) [L. 4].

![Fig. 2. Dependence of friction coefficient $f$ on total roughness of rubbing bodies $\Sigma R_z$: 1 – cast iron against steel; 2 – bronze against steel](image)

Rys. 2.Зависимость коэффициента трения $f$ от суммарной шероховатости трения $\Sigma R_z$: 1 – железо по стали, 2 – бронза по стали

![Fig. 3. Dependence of established (optimal) microgeometry on contact time of surfaces at different initial roughness](image)

Rys. 3. Влияние полученной (оптимальной) микрогеометрии на контактное время поверхностей при различных начальных шероховатостях

Wear resistance is influenced not only by the comb value, but also by their direction, methods to deform the combs, and the mechanical and physical state of the surface layer.

Structural heterogeneity of the surface layer should be reduced as far as feasible, and homogeneous stresses over the whole surface should be created in order to increase wear resistance during finishing. The influence of the roughness of the surface layer on its wear also depends on the form of irregularities. Fine and numerous irregularities provide more wear resistance than large coarse-pitch irregularities (Fig. 4) [L. 3].
Knowledge of nature and extent of the impact of surface layer parameters on performance characteristics allows solving the problem of surface layer quality control in order to create the required characteristics of performance properties by selecting cutting conditions and tool geometry providing the specified values of surface layer parameters. In the context of the setting of cutting conditions in terms of surface layer state when machining heat-resistant alloys, it is efficient to define cutting conditions providing optimal temperature in the cutting area and minimal cutter wear is observed. Cutting rate corresponding to the optimal cutting temperature is called optimum speed. In this case, more favourable indices of surface layer state are provided. When machining in optimal cutting modes, the value of the height of machined surface irregularities, the minimal depth and degree of cold working, which in some cases are needed in the surface layer of the machined part, turn out to be minimal or become minimally stable (Fig. 5).

Under optimal cutting conditions, i.e. in the conditions corresponding to the optimum temperature, the value of the approach of part contact surfaces has minimal magnitude; therefore, the strength of contact has a maximal value (Fig. 6).

When cutting mating surfaces, the most influences on the compliance factor and therefore on contact stiffness are exert by the following parameters: feed $S$, cutter tip radius in the plan $r$, and tool tip corner radius $\rho$. The same parameters exert considerable impact on the roughness of the machined surface. The cutting depth exerts insignificant influence on the contact stiffness of the machined surface.

Fig. 5. The dependence of surface roughness $R_z$, microhardness $H_d$ and depth of cold working $h$ on cutting rate. Milling of alloy XH50BMKTIO with milling cutter made of P18: $S = 0.08$ m/rev; $t = 1 \cdot 10^{-3}$ m; $\alpha = \gamma = 10^\circ$

Rys. 5. Wpływ chropowatości powierzchni $R_z$, mikrotwardości $H_d$ i głębokości utwardzenia $h$ na wydajność skrawania. Obróbka stopu XH50BMKTIO narzędziem wykonanym z P18, $S = 0.08$ m/obr.; $t = 1 \cdot 10^{-3}$ m; $\alpha = \gamma = 10^\circ$

Fig. 6. The dependence of the approach of contact surfaces $y$ on cutting rate under their machining: $a = 10^\circ$; $\phi = 45^\circ$; $\phi l = 15^\circ$; $r = 1$ mm; $S = 0.2$ mm/rev. Work material VT9, $\gamma = 0^\circ$. Work material 13X12HBMFА, $\gamma = 10^\circ$.

Rys. 6. Wpływ zbliżenia stykających się powierzchni $y$ na wydajność skrawania przy parametach: $a = 10^\circ$; $\phi = 45^\circ$; $\phi l = 15^\circ$; $r = 1$ mm; $S = 0.2$ mm/obr. Materiał obrabiany VT9, $\gamma = 0^\circ$. Materiał obrabiany 13X12HBMFА, $\gamma = 10^\circ$. 

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The formula to determine compliance, i.e. the approach of part contact surfaces depending on cutting parameters, is as follows [L. 5]:
\[
\omega = \frac{35 \cdot 10^{-7} S^{1.1}}{r^{0.8} \rho_1^{0.66} t^{0.175}}, \text{ m/N},
\]
where the following dimensions are specified: \( S \) in mm, \( r \) in mm, \( \rho_1 \) in \( \mu \text{m} \), \( t \) in mm.

The problem to determine the parameters characterizing the cutting process according to the given compliance value can also be solved [R. 6]. For example:
\[
S = 0.09 \omega^{0.91} r^{0.73} \rho_1^{0.6} t^{0.1} 10^{6}, \text{ mm}.
\]

For specific combinations of the machined material and the tool material under the tool geometry recommended for optimal machining conditions, the value of the wear intensity of the contact surface can be determined by the following formula:
\[
I_h = 0.036 \left( \frac{0.5 \varepsilon ^{2.1}}{n} \left( \frac{c S^{n}}{r^{0.5} \rho_1^{n_0}} \right)^{0.874} \right),
\]
where \( \alpha_a \) is the coefficient depending on the contact type. At elastic contact \( \alpha_a = 0.5 \), and at plastic contact \( \alpha_a = 1 \), \( \varepsilon \) is the relative approach of contact surfaces expressed through proportions of maximal profile irregularity height; \( n \) is the number influence cycles resulting in material destruction; \( S \) is the feed, mm/rev; \( r \) is the tool point radius, \( \mu \text{m} \); \( \rho_1 \) is the tool tip corner radius, \( \mu \text{m} \).

In the general case for conditions of optimal cutting [L. 7] the following formula is used:
\[
I_h = \frac{10^3 a_2^{0.5} \varepsilon_1^{2.1}}{m^0.874} \times \left\{ 0.6625 a_1^{0.125} \left[ 4.3 \sin(\alpha) \right]^{0.115} v_0^{0.57} a^{0.345} \lambda \left( \frac{t}{m} + \lambda_p \beta \epsilon a^{0.57} \rho_1^{0.075} \right) c_p \theta_0 \right\}^{1.75} \left( \frac{1}{1-\varepsilon} \right),
\]
where \( a, t \) is the thickness of cut and the depth of cut in machining; \( v_0 \) is the optimal cutting rate; \( \alpha, \gamma \) are the back clearance and the front clearance angles of the tool cutting part; \( a \) is the temperature diffusivity of the material of the machined part; \( \lambda, \lambda_\epsilon \) are the thermal diffusion coefficients of the machined material and the tool material; \( \beta, \varepsilon \) are the cutting point angle and the cutter tip angle in the plan; \( r, \rho_1 \) are the cutter tip radius in the plan and the tool tip corner radius; \( c_p \) is the volumetric specific heat capacity of the machined material; \( \theta \) is the temperature in the cutting area; \( \tau_\epsilon \) is the resistance of the machined material to the flow shear; \( b \) is the length of the tool tips-part contact; \( m \) is the dimensionless value depending on the feed-cut depth ratio, as well as on the tool point geometry parameters; \( c_\alpha, n_0 \) are the constants for a particular combination of the machined and the tool materials.

For the given value of wear intensity for conditions differing from the optimum, the feed is determined by the following formula:
\[
S = \frac{b^{0.7} c_p \theta_0 \rho_1^{0.1} a^{0.43} \left[ 2.85 \sin(\alpha) \right]^{0.115} v_0^{0.57} a^{0.345} \lambda b^{0.3} + 0.6625 \lambda_p \beta \epsilon a^{0.57} \rho_1^{0.075} \left[ a_1 \right]^{0.165}}{\left[ \left( 1 - a_2 \cdot B^{-b_2 \left( 1 - \sin(\gamma) \right)^{-x}} \right) + a_2 \cdot B^{b_2 \left( 1 - \sin(\gamma) \right)^{-x}} \sin(\alpha) \left[ \cos(\gamma) + B \sin(\gamma) \right] \right] - \cos \alpha} \right] \left[ \left[ m \cdot \frac{0.125}{\sqrt{\sqrt{2} r \cdot \varepsilon_0}} \left[ 1 + \frac{1}{B} + \tan \left( \arctan B - \gamma \right) \right] \cdot \frac{28 I_h}{\alpha_2^{0.5} \varepsilon_1^{2.1}} \right]^{-0.808}\right]^{8},
\]

where \( m = \frac{\rho_1}{S} \).

**CONCLUSION**

Thus, based on the theoretical research, it is possible to determine the tribotechnical characteristics of machined surfaces or the machining conditions providing the specified performance characteristics by calculation.
REFERENCES