Advances in Engineering Research, volume 188

International Conference on Aviamechanical Engineering and Transport (AviaENT 2019)

Process Control of Forming the Surface Quality Parameters of Parts According to a Desired Law by Methods of Surface Plastic Deformation

Nagorkin M. N.
Department «Safety of life activity and chemistry»
Bryansk State Technical University
Bryansk, Russia
e-mail: nagorkin@tu-bryansk.ru

Fedorov V. P.
Department «Mechanical Engineering Technology»
Bryansk State Technical University
Bryansk, Russia
e-mail: fedorov.tm.2017@yandex.ru

Kovalyova E. V.
Department «Tribotechnical Materials Science and Engineering»
Bryansk State Technical University
Bryansk, Russia
e-mail: lenako1965@mail.ru

***Abstract* - The paper deals with ways to process control of forming the surface quality parameters according to a desired law with the help of machining by surface plastic deformation on CNC machines, which allows ensuring the uniformity of surface operational properties when working in conditions of unstable operating loads. There are also considered operational features of functional surfaces in sliding friction connections of machinery and technological equipment, and models of changing power and velocity factors of operation. The dependences allowing determining the values of machining factors to ensure the changing quality parameters are presented. Also there are results of process control of forming the flat surface quality parameters due to technological inheritance of quality parameters obtained at the stage of pre milling with composite 10.**

Keywords – operating conditions, controlled machining factors, quality parameters, diamond burnishing, technological inheritance

I. Introduction

During operation, connection parts are exposed to a number of random factors that lead to an uneven change in the operational properties of functional surfaces with the uniformity of their quality. One example is uneven wear of guide members such as sliding friction technological equipment and tooling (bed frame, bars, rods, etc.), due to the interaction of quality uniformity of functional surfaces with the instability of operating conditions. The result is a loss of connection accuracy as one of the most important functions of technological equipment.

Uneven change of surface operational properties is connected with the fact that constant machining conditions are specified during operating steps, at the same time, uniform parameters of surface quality are formed. The proposed approach to process control allows creating quality parameters, varying according to the machined surface, which covers the corresponding changes in its tribotechnical characteristics during operation.

Machining of parts while solving the problem of adapting the surface to variable operating conditions must be flexible. To do this, it is recommended to use technological methods which within operating steps allow to change the values of control factors, such as power (static, dynamic), kinematic (speed, supply), electrophysical (current strength, pulse duration), etc.

There are no practical recommendations to ensure the required properties of surfaces operating in non-stationary conditions, which emphasizes the relevance of research in this direction, as their results can make a significant contribution to surface engineering, associated with increasing reliability and durability, and, consequently, the growth of product quality.

II. Results and Discussion

The analysis of technological support of triboelement wear resistance shows [1 – 3], that authors often consider operating parameters (P is pressure per unit of bearing projected area; V is resultant sliding velocity of triboelements) as constant values, stable in space and time and having a fixed minimum and maximum values.

For reciprocating sliding couples, including a wide range of technological equipment and tooling guides (from v-guides to cylinder guides) it is typical to have a change of normal load P and resultant sliding velocity V, as functions continuously changing in space and time. A detailed analysis of the changes of functions P and V in space and time is given in [4, 5, 6], on the basis of which the typical laws of changing these factors in space for friction couples of slide guide type are defined (Fig. 1).

The most common law of changing load P in space is a trapezoid one (case P1, Fig. 1), which is characterized by loading section ax_1, operation under maximum load P_0 (x_1x_2 section) and unloading x_2b.

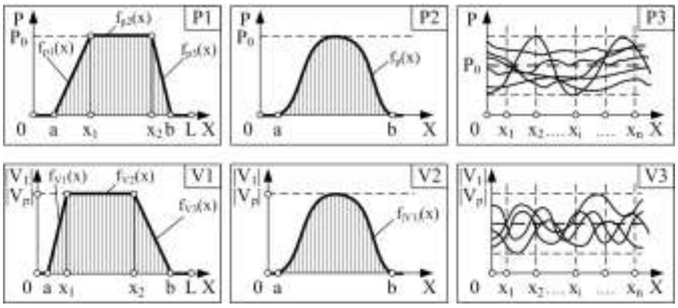

Fig. 1. Typical laws of changing load P and resultant sliding velocity V in space for friction couples of slide guide type

And dependence of load change in space of the surface coordinates of basic triboelement X can be described by different equations for different sections such as $f_{p1}(x)$, $f_{p2}(x)$ and $f_{p3}(x)$, the analytical form of which is determined by the specific operation of the connection.

A simpler case is P2 (Fig. 1) when dependence $f_p(x)$ is a continuous differentiable function having a general analytic description.

Case P3 (Fig. 1) is the dependence of load P in the form of a stationary random process in the function of surface coordinate X.

When considering resultant sliding velocity V of triboelements, its absolute value should be taken into account, since the specific operation of slide guides of technological equipment and other machines determine its variableness. The most common is also a trapezoid law of dependence of mobile triboelement speed on the coordinates of the selected point of the basic triboelement (case V1, Fig. 1). This case is also characterized by the presence of acceleration section ax_1, x_1x_2 section of tribosystem operation at a speed close to maximum (random fluctuations are possible), and deceleration section x_2b.

Case V2 (Fig. 1) is characterized by the possibility of interpreting the dependence of mobile triboelement speed $|V_1|$ on the current coordinate X of the selected point of the basic triboelement by the continuous differentiable analytical function. Speed $|V_1|$ can be a stationary random function of coordinate X (case V3, Fig. 1), which is characteristic of the movement of tribosystems at low speeds, when there may be cases of deceleration and acceleration, for example, in relation to setting processes.

The analysis given shows that in order to ensure even wear of the guide surfaces of machine parts, as well as technological equipment and tooling, when developing the technology for machining their functional surfaces, it is necessary to take into account the peculiarities of affecting operational factors on them, in particular the load and resultant sliding velocity of triboelements, to form the appropriate parameters of their quality by means of software [4, 5, 6].

The proposed graph model of forming quality and operational properties of triboelement surfaces (Fig. 2) [5] shows in the form of nodes the states of triboelement functional surfaces S_0 ... S_4 for different levels of the life cycle (I ... III) and directed edges of U_{ij} transitions from i-node to j-node, characterized by the functions from the spatial coordinate X (for example, the length of the flat sliding friction guide) and additional parameters characterizing the sets of machining conditions $\overline{R}$, surface layer quality parameters (SLQP) $\overline{K}$, operating conditions $\overline{P}$ (load, resultant sliding velocity, temperature, dynamic factors, etc). Graph nodes S_1 and S_3 correspond to isotropy, and nodes S_2 and S_4 correspond to anisotropy of quality (S_1, S_2) and parameters of operating properties (S_3, S_4) of triboelement functional surfaces.

As a result of technological support of operating properties (OP) of machine element surfaces, two nodes of the graph model are possible: S_3 where parameters of operating properties are not function X and are constant; S_4 where parameters of operating properties are function X and are variable.

Minding the requirements of the consumer to the product quality, the most popular is state S_3. In modern production conditions it can be achieved in accordance with the logical requirement

$$S_3 = (U_{01} \wedge U_{13}) \vee (U_{02} \wedge U_{23}). \tag{1}$$

Until recently the following evolution way of the initial surface state S_0, which is considered consistently isotropic, to the operational state S_3 has been traditional:

$$S_0 \xrightarrow{U_{01}} S_1 \xrightarrow{U_{13}} S_3. \tag{2}$$

In practice, however, there are situations where the operating conditions $\overline{P}$ of triboelement compounds are transient. In this case, functional surfaces with stationary quality parameters $\overline{K}$ = const, under the influence of transient operating loads $\overline{P}$ = var are characterized by a transient vector of operating properties, corresponding to the state S_4 on the graph model (Fig. 2), which can be achieved in the following way (3):

$$S_0 \xrightarrow{U_{01}} S_1 \xrightarrow{U_{14}} S_4. \tag{3}$$

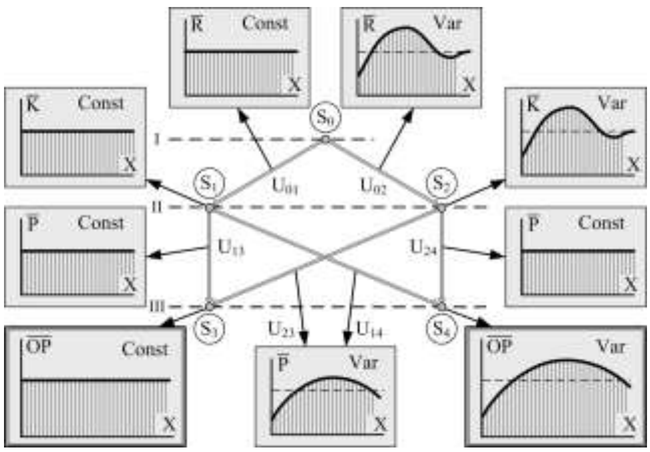

Fig. 2. Model of forming quality and operating properties of triboelement functional surfaces: I, II, III are initial, technological and operational levels; $\overline{R}$, $\overline{K}$, $\overline{P}$, $\overline{OP}$ are vectors of machining conditions, parameters of surface layer quality, operating conditions and parameters of operating properties respectively; X is a coordinate of an impact point on triboelement surface

To ensure stationary and consistent OP characteristics, that is, their isotropy on the triboelement surface, it is necessary to provide technological support for the regular change of corresponding SLQ parameters at the appropriate surface coordinate, in other words, their required anisotropy. This can be done in the following way (4):

$$S_0 \xrightarrow{U_{02}} S_2 \xrightarrow{U_{23}} S_3. \quad (4)$$

To implement this is an actual engineering problem in the field of technological support of operating properties of machine elements. Its solution is facilitated by solving a number of accompanying tasks, in particular:

1. Determination of space-time regularities of operating factors influencing the link ($P_i = f_{i1}(X)$, $P_i = f_{i2}(t)$), and characterizing transient operating conditions.

2. Identification of corresponding regularities of changes in SLQ parameters on the triboelement surface in the function of its coordinate $X(K_i = f_i(X))$, which can compensate for transient operating conditions and ensure the surface state S_3, that is, its isotropy in the parameters of operating properties.

3. Formation of a range of effective technological methods of machining, allowing to implement the required changes in the quality parameters values (work hardening, residual stresses, roughness, etc.) in the function of the work surface coordinates ($K_i = f_i(X)$), that is, U_{02} way is implemented, solving the problem of reaching node S_3 (Fig. 2), and, consequently, the problem of achieving surface isotropy in terms of operating properties under transient operating

To solve task 1 it is advisable to take into account the following prerequisites: during operation of sliding couples on the surface of triboelements generally there can be following types of loads from element 1 (Fig. 3):

1) static load ($P_1 = P_0 = const$);

2) dynamic load P_2, which in a particular case may have amplitude *ap* and period T;

3) P_3 is load as a stationary random function with expectation $M\{P_3\} = P_0 = const;$

4) $P_4 = F(X)$ – normally changing (with extremum or monotone);

5) P_5 – the load as a non-stationary random function with expectation (in the case of Fig. 3b $M\{P_5\} = P_4$) depending on X coordinate of element 1.

The type of load transferred to the functional surface of the element does not uniquely determine the operating conditions of the connection. One of the important factors determining surface wear diagram h is the distribution function $f(x)$ of coordinate X of mobile triboelement 1. Surface wear value h will be equidistributed at static load P_1 and uniform loading function $f_1(x)$. It is assumed that SLQ parameters are distributed isotropically over the surface. At any steady load (P_1, P_2, P_3), but with distribution functions $f_i(x)$ of element 1, different from function $f_1(x)$, wear value h of surface will be distributed unevenly. This generally results in a loss of precision of the technological equipment.

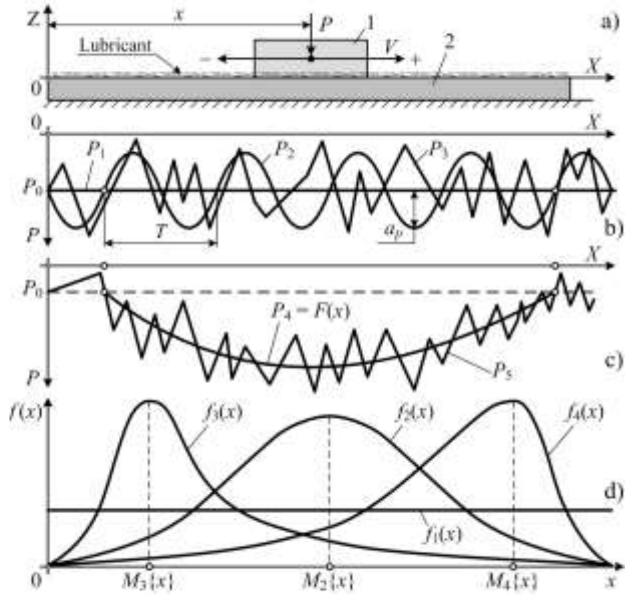

Fig. 3. Types of interaction between the elements of sliding couple connection: a is connection model; b, c are possible types of operating loads P; d is distribution laws of coordinate X of element 1 (sliding ram)

The worst situation occurs when there are unsteady loads P_4 and P_5 and distribution function $f_2(x)$ of element 1 relative to surface. At the same time in the neighborhood of point $M_2\{x\}$ ($X = M_2\{x\} \pm k\sigma(x)$) there will be increased wear, which value is proportional to function $F(X)$.

All this is related to cylindrical sliding friction guides.

Thus, the stability of the operating conditions of sliding friction connections is characterized by load $P_i = F_i(x)$ and the distribution density of its application point to surface $f_i(x)$.

The solution of problems 2 and 3 requires the possibility of changing machining modes in forming elementary surface, which is functional with a desired law of changing quality parameters in space. This means that machining conditions must be controlled within the transition, which can be implemented in technological systems with a sufficiently high technological flexibility, which is understood as the ability to provide a given set of SLQ and OP parameters in regulated intervals with established reliability by directional variation of machining conditions and controlling technological inheritance.

Two kinds of technological flexibility of processing systems should be distinguished [5]:

1) technological flexibility of the 1st type: it is possible to choose surface machining methods for the final operations of the production process and for a group of controlled factors of each method, constant in value within the corresponding transition and providing surface isotropy according to the regulated values of SLQ parameters within the specified limits and with the required reliability;

2) technological flexibility of the 2nd type: it is possible to choose surface machining methods for the final operations of the production process and for a group of controlled factors of each method, one or more of which can be software controlled

within the transition according to the law that provides desired anisotropy of distribution of SLQ and OP parameters of the machined surface with the required reliability.

Technological flexibility of the 2nd type is inherent in CNC systems, where it is possible to change the machining conditions (factors) by software within the transition or complex technological systems in which one or more subsystems are provided with CNC equipment.

For the systems with technological flexibility of the 2nd type, it is advisable to introduce degrees of freedom, the number of which corresponds to the number of factors of machining modes that can be software-controlled within the transition. The concept of degrees of freedom for a system with technological flexibility of the 2nd type can be explained in the following way (Fig. 4) [5].

When face milling by means of a CNC machine a flat functional surface of work piece 1 (Fig. 4a) within the transition, it is possible to control only one feed parameter $S = X_1$, provided that the size h is maintained. Therefore, it is a system with one degree of freedom.

An example of machining with two degrees of freedom can be rolling (diamond burnishing) by means of CNC machine that provides software control within the transition by two machining factors: feed rate $S = X_1$ and power $Q = x_2$ (Fig. 4b).

Electromechanical processing (Fig. 4b) is an example of a technological system with three degrees of freedom: feed rate $S = X_1$, machining force $Q = x_2$ and current force $I = X_3$, passing through the contact area between the indenter and the machinable surface if there is device 3 of software controlling current force.

It is obvious that an important factor of machining is the degree of its technological flexibility, which should be calculable. If we take machining modes for turning (*V*, *S*, *t*) and for the methods of surface plastic deformation (SPD) (*Q*, *S*, *V*), then there are three controlled factors in each case, but the technological flexibility of SPD process is much higher: in this case, all SLQ parameters (macro- and microgeometry, physical and mechanical properties, etc.) can be controlled in a much wider range and more reliably than in turning. The use of any system often contributes to forming completely new properties, not peculiar to the basic component material.

As an example of implementing the system of increased flexibility can serve a technological system for machining components such as sliding guides, including finishing face milling with composite 10 (Fig. 4a) and SPD machining by diamond burnishing (DB) or ball rolling (Fig. 4b), and their software control allows to provide a desired law of changing quality parameters on the machined surface.

For SPD there were used elastic action tool tools with the indenter made of polycrystalline diamond ASPK or a ball (SHKH15) [4, 5, 6].

While machining components by means of CNC and PCNC machines and four factors can be controlled:

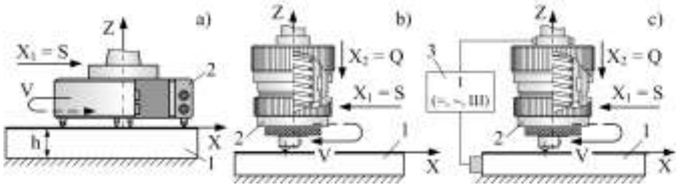

Fig. 4. Examples of machining flat surfaces in systems with technological flexibility of the 2nd type: a is face milling by composite 10; b is diamond burnishing or rolling by springing tool; c is electromechanical processing by springing tool; 1 is a workpiece; 2 is a tool; 3 is a programmable source of constant, alternating or impulse voltage

– for milling: cutting depth *t*, machining speed *V* and feeding speed S_X and S_Y, due to them the initial surface quality is formed;

– for SPD methods: indenter impact force *Q* on the machined surface, machining speed *V*, feeding speed S_X and S_Y, which, with the selected type of indenter and its radius *r*, provide the required surface quality parameters that vary according to a desired law, taking into account technological inheritance [1.5, 7].

The study of this technological system allowed to obtain a connection between quality parameters with the machining conditions:

$$R_i = b_{0i} Ra_{pr}^{b_{1i}} Q^{b_{2i}} S_{SPD}^{b_{3i}}, \qquad (5)$$

where R_i is *i*-quality parameter (R_a, R_p, etc.); Ra_{pr} is the surface roughness parameter after pre milling; *Q* is the indenter force; S_{SPD} is the indenter feed during SPD machining; b_{0i} ...b_{3i} are corresponding coefficients of the model.

If a specified value of quality parameter R_{isp} is a function of the machined surface length and for each area of the machined surface x_i it should be of a certain value $R_i(x_i)$, then this is achieved, for example, due to changing *Q* force in SPD machining which is defined as (5):

$$Q(x_i) = \left(1 \Big/ b_{01} Ra_{pr}^{b_{11}} S^{b_{31}} \right)^{1/b_{21}} \cdot R_{i\,sp}(x_i)^{1/b_{21}}. \qquad (6)$$

The values of coefficients b_{01} ... b_n are taken from reference data or obtained by diagnostic methods of a specific technological system for SPD machining [5].

It is possible to control $R_i(x_i)$ parameter by means of technological inheritance. In this case, the roughness of the premachined surface on i-section should be:

$$Ra_{pr}(x_i) = \left(1 \Big/ b_{01} Q^{b_{21}} S^{b_{31}} \right)^{1/b_{11}} \cdot R_{i\,sp}(x_i)^{1/b_{11}}. \qquad (7)$$

In mechanical engineering there are cases of the impact of operating factors in the form of a trapezoidal law of load distribution on the functional surfaces of components such as sliding guides. Accordingly, the use of the trapezoidal law of changing *Q* force in SPD machining will be effective.

In this case (Fig. 5) typical is the presence of acceleration segment x_1, stable impact of external factors x_2 and deceleration segment x_3. In these segments, machining force Q should change respectively.

When developing and implementing the program that provides a trapezoidal law of controlling Q force, along with parameters x_1, x_2, x_3 initial data are the values of minimum and maximum force (Q_{min}, Q_{max}), tool spring force, the feed value S and machining speed V. Coordinates X_0, Y_0, Z_0, characterizing the workpiece position in the machining zone before machining, are also considered as initial data.

The values of Q_{min}, Q_{max}, x_1, x_2, x_3, as well as laws $Q = f_1(x)$ and $Q = f_3(x)$ are initial data for technological design and are calculated by the designer based on actually expected unstable operating conditions [8].

It is also convenient to control the change in surface quality during SPD machining according to a desired law by means of corresponding change in the feed within the transition along the hardening route. This method is easily implemented in CNC or PCNC computer control systems.

Flat surfaces of workpieces of $L \times B$ size are easily machined by SPD method, according to program "Meander" (Fig. 6). Here l is the technological size, r is the radius of rotation of the elastic action device springing tool indenter for SPD (Fig. 6a).

Since the machining program is based on ISO-7bit program code, the feed has F value.

Analytically, the change in feed F is defined by the equation according to alternating rule:

$$F = F_{\min} + (F_{\max} - F_{\min}) \left| \sin\left(\frac{2\pi}{t_F} X\right) \right|, \qquad (8)$$

where X is current point coordinate within feed change t_F.

In general, the rule (8) can be any, but the only requirement for it is analytical dependence of feed value on coordinate X. This dependence can be stochastic, but in this case it is necessary to know the distribution law parameters of random feed value within t_F period. Then the solution of this problem is not difficult.

Depending on the initial data machining tracks (Fig. 6a) may overlap and not overlap. If this is not regulated in advance, the current overlap ratio is calculated during machining:

$$k = \frac{1}{r}\left(2r - \frac{B - 2(\ell + r)}{N - 1}\right).$$

where N is a number of machining tracks (Fig. 6a: N = 3).

Control of forming the surface with areas of different quality by means of technological inheritance is considered effective. The easiest way to control is preparatory finishing (in this case, face milling by composite 10) with different feed on surface areas I and II (Fig. 7).

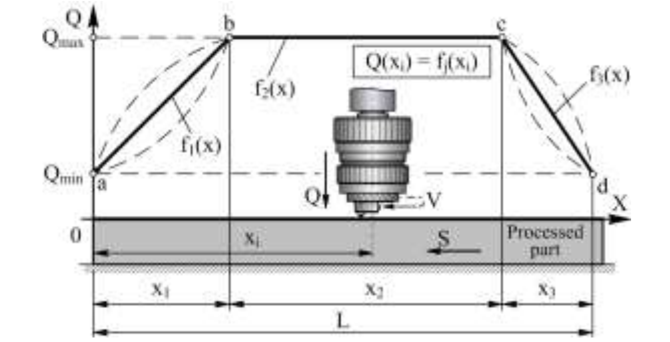

Fig. 5. Trapezoidal law of changing Q force in SPD machining of flat surfaces by springing tool

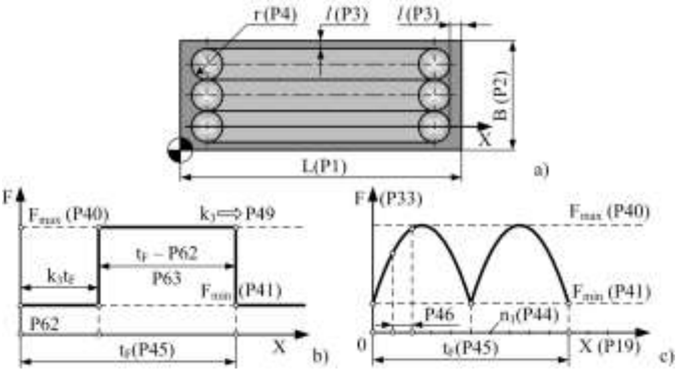

Fig. 6. SPD machining of surfaces according to program "Meander" with intermittent feed: a is machining pattern; б, в are step and alternating rules of changing feed along axis X

Here, a simple change in the feed value during pre machining (face milling) due to static and dynamic properties of the technological system automatically leads to the appearance of the stage ΔH_1 (Fig. 7a).

ΔH_1 value depends on many factors that can be controlled. These include tool geometry and machining modes (speed, feed, depth). But one of the most important factors is the technical condition of technological system, characterized by its static and dynamic inflexibility.

During subsequent diamond burnishing of the initial surface in the transition area (II – I), stage ΔH_2 is formed (Fig. 7b), which, taking into account stage ΔH_1, is also determined by the current conditions of SPD machining, including the initial quality of the machined surface $R_{ucx\text{I}}$ and $R_{ucx\text{II}}$ as well as SPD modes (in this case Q and S_{DB}).

In the course of pre machining on the transitions (I – II) it is necessary to make a correction in tool Z-direction $\Delta Z = f(\Delta H_1, \Delta H_2)$ to eliminate differentials on section boundaries I – II after SPD machining. If preparatory finishing and final SPD machining are implemented in the same technological system, then it is practically accurate to make correction $\Delta Z = \Delta H_2$ (Fig. 7 b) (here $\Delta H_2 \approx 11$ μm).

Further machining by means of diamond smoothing forms the final surface with differential $\Delta H \approx 0$, but with different quality parameters in areas I – II (R_1, R_2), (Fig. 7d) and various microtopography of these surface areas (Fig. 7e).

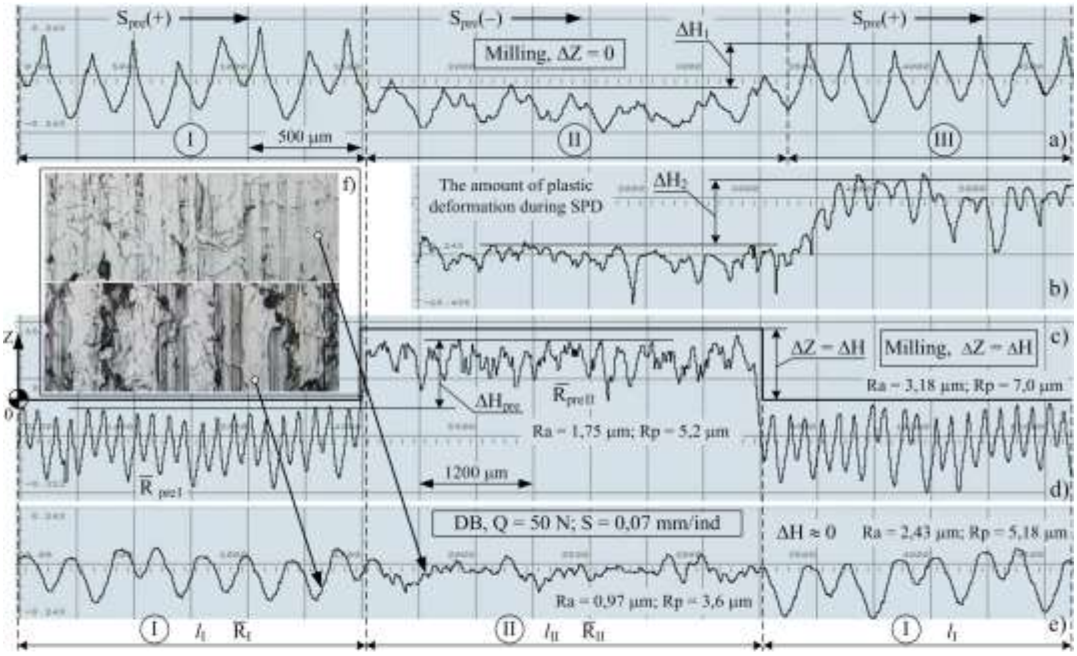

Fig. 7. Forming the component surface with different quality areas by means of technological inheritance

III. Conclusion

Taking into account that most of actual tribotechnical systems operate under instable operating conditions, we propose a scientifically based approach to the technological support of regular changing surface quality parameters of components, ensuring the consistency of surface operational properties while working in nonuniform conditions on the basis of regular control of machining modes on CNC machines. A model of software control of forming regular changing surface quality of components is developed, and technologically flexible systems are proposed, allowing software control of one or more machining factors (feed, SPD power, etc.) within the transition.

The research results can serve as a starting point for further theoretical development of technological support of the required diagram to distribute quality parameters on the component surface during machining and practical implementation of these results. For this purpose it is necessary to solve a number of tasks: 1) to develop standards or guidelines to regulate in technological documents the required diagrams of distributing quality parameters on the functional surfaces of critical parts; 2) to develop software and hardware for technological support of a given quality diagram on the part surface during machining for the real production, etc.

References

[1] "Surface Engineering," authors group; under the editorship A.G. Suslov, Moscow: Mechanical Engineering, p. 320, 2008.

[2] "Technological maintenance and increase of operational properties of details and their connections," A.G. Suslov, V.P. Fedorov, O.A. Gorlenko and etc., under the editorship A.G. Suslov, Moscow: Mechanical Engineering, p. 447, 2006.

[3] A.O. Gorlenko and S.P. Shetz, "Investigation of kinetics of wear in friction pair of type "undercuff neck-cuff edge," Lecture notes in mechanical engineering, Proceedings of the 4th international conf. on industrial engineering, ICIE-2018, vol. 1, pp. 765-772, 2019.

[4] M.N. Nagorkin, V.P., Fedorov and A.V. Totay, "Exploitation conditions of functional surfaces of details in standard connections of a sliding friction," Proceedings of the Southwest state university, vol. 6 (57), pp. 15-26, 2014.

[5] M.N. Nagorkin, V.P. Fedorov, V.V. Nagorkina and E.V. Kovalyova, "Parametric reliability of processing systems for edge cutting machining and strengthening machining with tools of synthetic ultra-hard materials according to geometric parameters of quality and tribotechnical characteristics of parts surfaces," in Modern engineering technoques, equipment and toolware, vol. VII, Under the editorship A.V. Kiricheck, Moscow: Publishing house Spektr, 2016, pp. 506-688.

[6] V. P. Fyodorov, V. I. Averchenkov, M. N. Nagorkin, "Controlling the parameters of the component quality using program means while performing mechanical machining," Procedia Engineering, 2nd International conference on industrial engineering, ICIE-2016, vol. 150, pp. 899-905, 2016.

[7] O.N. Fedonin, S.V. Steposhina, "Scientific basis of the choice of machining conditions at surface plastic deformation," Bulletin of Bryansk state technical university, vol. 1, pp. 4-8, 2011.

[8] A.G. Suslov, O.N. Fedonin, E.A. Polskiy, "High technology of improving the quality of assembly units of machines at the stage of the life cycle," Science intensive technologies in mechanical engineering, vol. 5 (59), pp. 34-42, 2016.