Surface profiling in mating parts by combined nonabrasive finishing

EV Smolentsev¹, ON Fedonin² and VP Smolentsev¹,

¹ Voronezh State Technical University, 14, Moskovsky ave., Voronezh, 394026, Russia
² Bryansk State Technical University, 7, 50-letiya Octyabrya bul., Bryansk, 241035, Russia

E-mail: smolentsev.rabota@gmail.com

Abstract. Nonabrasive finishing of precision mating surfaces in locking devices with the use of a combined erosion-chemical process at the first stage of the processing and with the use of anodic dissolution by alternating low-voltage current at the final stage of a refinement operation till gapless joints obtaining is considered. It is shown that the application of electroerosion, electrochemical and combined nonabrasive finishing in mating parts opens up a possibility to ensure stable impermeability in locking devices on a macro- and micro-level through the method of a substantiated purpose of technological modes. A procedure is created for the development of such modes, and on their basis technological processes for the obtaining of gapless mating surfaces meeting the performance requirements for locking devices are developed. For this purpose, qualitative devices resistant to hostile environment are manufactured that is urgent for the mechanical engineering including repetition work for the equipment of petrochemical industry, transport and household machinery.

1. Introduction
Mating units with different systems of impermeability are used in the equipment which excludes falls of the flows of liquid and fluid media at small pressure at the expense of elastic seals (rubber and plastic rings, stuffing-boxes and so on), and washers. But with the pressure increase at the input, the sealing element wear increases, and the reliability and life of sealing elements decrease. Therefore, if pressure difference reaches tens of megapascals, then to ensure impermeability one begins to use seals with discharging chambers of the type shown in [1]. But the field of their application is rather limited, and for many locking devices with high pressure (particularly in aggressive flowing media), they are ineffective.

In the majority of locking devices used, it is necessary to ensure high accuracy and indices of a surface layer in mating movable parts. For high-pressure devices, a mutual processing of these surfaces without abrasive use which can charge the places of mating, cause increased wear, create gaps and cause the leaks of pumped media is required. At the same time, the errors in mating areas must be commensurable with a height of micro-roughness, and a width of micro-defect opening of a surface layer must not exceed tens of nanometers.
2. Analysis of mechanical finishing operations

In Table 1, the technological values and requirements for mechanical finishing operations are shown in [2].

| Stages of finishing | Technological potentialities and requirements |
|---------------------|----------------------------------------------|
|                     | Allowance, µm | Error, µm | Roughness (Rz), µm |
| Preliminary         | 20-50         | 3-5       | 3.2-0.8           |
| Medium              | 5-20          | 1-3       | 0.8-0.4           |
| Final               | 2-5           | 0.5-1.0   | 0.4-0.1           |
| Fine                | 2-0.2         | 0.1-0.5   | 0.1-0.02          |

The analysis of Table 1 allows justifying a choice of a rational technological method of processing for each stage of precise surfaces finishing including mating ones.

One of the ways for a controlled removal of imperfections in the areas of locking elements consists in the use of a contactless processing with the superposition of an electric field. But technological problems arise here since electro-erosion finishing ensures obtaining the roughness (Rz) not less than 0.8-1.0 µm, which is unacceptable for many locking devices.

An anodic process with a recommended voltage range not lower than 5-6 V also does not make it possible to obtain the required accuracy (within parts of the micrometer) and roughness (minimum value Rz is about 0.1µm). Furthermore, before the beginning of a finishing operation, each of mating surfaces may have an error of 5-10 µm which requires allowance removal with the value not less than a limit value of tolerance for a blank at the first stage of finishing. For this purpose, the use of electro-erosion processing with ‘soft’ technological modes increases considerably labour-intensiveness of an operation and forms a cellular surface on each mating element unsuitable for locking devices. Besides, the low voltage, used in this case, violates the process stability and causes the appearance of local micro-defects and imperfections with a height greater than it is allowed by requirements of a drawing. A contactless anodic dilution does not allow ensuring accuracy in the areas of mating and at recommended voltages below breaking ones [3], it is impossible to reduce an initial height of roughness, that is, to obtain surfaces with required indices after finishing at a nano- and microlevel.

The works carried out have shown that during nonabrasive finishing of mating movable surfaces it is expedient to use two stages of processing: the first stage is with the use of a combined erosion-chemical process with direct current with a polarity periodical change, the second stage - at low-voltage anodic dissolution of micro-imperfections of alternating current with mechanical depassivation of the area of parts mating. In the latter case, the voltage on electrodes decreases up to 3-4 V at the expense of losses during the removal of a passivating film removed partially by a mechanical impact of a moving opposite mating surface of a locking device.

3. Mating surfaces geometry

In the equipment, mating surfaces of several types are used; some of them are shown in Figure 1. The process flow-sheets of the locking device grinding have significant differences. For the flat units (Figure 1 a), there is a typical possibility to control a pressing force of contact elements (gate 3 and nipple face 4) by means of changing elastic properties of part 5 (for instance, a spring). Besides, a swinging movement (‘A’ in Figure 1 a) allows supporting a constant position of an operation track on a gate during finishing and stabilizing a rate of a swinging movement of contact elements.
These surfaces, as a rule, are subjected to chemical-thermal treatment (for instance, nitration), that is why an allowance for their finishing should not exceed 50 µm. Similar locking devices can have face contact elements closing a saddle. In case of high pressures and expenses, in such elements, hydraulic impacts, breaking a flow of working environment, can arise; that is why, they are used mainly in hydraulic networks with the pressure up to 20 MPa.

In case of cylindrical locking devices (Figure 1 b), in the course of the preliminary finishing, there are gaps formed between a rotation part (1) and a case (2) which are required to use at this treatment stage of a technological rotation part with its substitution for a standard part at the final stage of treatment. At this stage of finishing, there arise complexities with the adjustment of operation clearances and their support in the course of maintenance, particularly in a pumping hostile environment, considerable temperature differences between flowing liquid and a case of a locking arrangement.

Cone structures (Figure 1 c) are more convenient for finishing in our case including those without using abrasive tools, as they allow adjusting a pressing force in a bevel coupling (4) between a rotation part (1) and a case (3), and also replacing the reciprocating travels of contact elements (Figure 1 a) by a turning motion of rotation part 1 in case 3. But their use is limited by the environment consumption passing through a device.

Ball valves (Figure 1 d) are rather complicated in manufacturing, though they widen considerably operational potentialities of locking devices complementing them by the functions of mixers and some other capacities. Here, new constructs are required for the adjustment of gaps and expensive
equipment for manufacturing spherical contact surfaces. During their finishing, it is difficult to exclude the application of abrasive tools.

4. Mating parts finishing

All locking devices shown in Figure 1 can be produced by finishing without using abrasives by means of a two-stage micro- and macro removal of allowance by a combined method with the superposition of an electric field.

At the first stage, an erosion-chemical removal of macro- and micro-imperfections with the removal of projections occurs at the expense mainly of anodic dissolution of metal from tips of imperfections of both mating surfaces (Figure 2).

![Figure 2](image)

1; 2 – mating parts; 3; 4 – oxide film; 5 – low-conducting liquid medium; 6 – RC pulse generator; 7 – polarity switch; 8 – low-voltage current source; I-I; II-II – boundaries of mating surfaces after the first stage of processing; A-A; B-B – external surface of an oxide film; P – pressure upon mating surfaces; V – rate of mutual displacement of mating surfaces.

**Figure 2.** The scheme of mating surfaces processing.

In the environment of the weakly-conducting liquid (5) when approaching parts 1 and 2 up to the contact of oxide films 3 and 4, an electro-erosion microremoval occurs to boundaries I-I and II-II which can ensure the mating of components at the nano-level of accuracy. It is well-known [4] that during the combined treatment, the removal takes place mainly from an anode. If an initial roughness and error of one of mating surfaces is considerably higher than the other, then it is possible to carry out finishing with the polarity at which the first surface will be constantly an anode and the removal from the other surface can be at the expense of the current reverse half-wave. But in most cases of finishing the allowances are provided for both mating parts that is why a current polarity is changed from time to time by switch 7.

The boundaries of an oxide film (A-A and B-B) change the position of a contact area of mating parts, where pressing is controlled by pressure P. Depending on the pressure of parts 1 and 2 the thickness of a film in the areas of a contact becomes smaller. Here the resistance drops and an increased removal of imperfections at the expense of an electro-erosion constituent of the process take place. Simultaneously, during the combined treatment, an anodic dissolution of micro-projections takes place by means of the current of constant-current source 8. To ensure the continuity of a finishing process and a periodic replacement of operation environment in the area of treatment, parts 1 and 2 are moved with the velocity ‘V’.

Under the influence of electrical discharges upon the surface of mating parts arise imperfections in the form of spherical holes (Figure 3).
Some of them allow removing geometrical errors of a profile, other form micro-imperfections defining a surface smoothness ($R_z$ in Figure 3). An electro-chemical constituent of the combined process contributes to a micro-profile smoothing and reduction of imperfections up to a nano-level (at the final stage of smoothing). As it is shown in [3], the correlation between a diameter ($d_h$) and a depth of hole $h$ depends upon modes of working. And at the same time, the depth ($h$) defines the reserve of the liquid working medium and the duration of anodic process passing controlled by the rate of mating parts travel.

At the second stage of finishing, only the anodic dissolution is used at a low alternating voltage from source 8 (Figure 2) with primary removal from the place of holes mating formed after the first stage of treatment (Figure 3). Then, there is a surface formed with the accuracy and macro-imperfections at a nano-level. A mechanical depassivation of the area of processing and a low voltage from a current source allows avoiding the intercrystalline etching of a working area and reduces friction [5] between contacting surfaces.

5. Substantiation for finishing modes

In [3], a dependence is offered for the estimation of an area diameter of the discharge effect which for electro-erosion finishing can be approximated by the diameter of hole $d_n$:

$$d_n = K_0 \cdot \left( \frac{A_u}{\tau_u} \right)^m \cdot \tau_u^n,$$

where

$$K_0 = \frac{L}{S(m - 0.5n) + 0.5n}.$$

Here $L$, $K_0$, $m$, $n$ – empirical coefficients; $L$ – measuring, mm; $S$ – inter-electrode gap measurable with the thickness of an oxide film; $\tau_u$ – pulse duration; $A_u$ – pulse energy. For the RC diagram:

$$A_u = \eta_1 \cdot \frac{C \cdot U^2}{2},$$

where $\eta_1$ – coefficient of energy efficiency (According to [3], $\eta_1 \leq 0.4$; according to [4], $\eta_1 \leq 0.2$); $C$ – capacitor capacitance of pulse generator RC of the diagram; $U$ – voltage on electrodes (at very small gaps $U=10$-$20$ V).

$$\tau_u = \frac{1}{qf},$$

where $q$ – on-off time ratio of pulses assumed as the ratio of a repetition period to their activity changes within the range of 2-10 (specified experimentally); $f$ – frequency of pulse sequence.

Approximately:
\[ f = \frac{0.837}{RC}, \]
where \( R \) – adjustable resistance of a RC-generator.

In Table 2, there are data for a choice of coefficients.

| Material of mating surfaces | Numerical values |
|-----------------------------|------------------|
|                             | \( L \)          | \( m \)  | \( n \)  |
| Steel                      | 0.08-0.1         | 0.75-0.78 |
| Copper alloys              | 0.036-0.04       | 0.65-0.68 | 0.28-0.3 |
| Aluminum alloys            | 0.097-0.1        | 0.7-0.75  | 0.3-0.35 |
| Cast iron                  | 0.18-0.2         | 0.8-0.82  | 0.35-0.4 |

For the definition of pulse energy, it is necessary to determine a value of a minimum spark gap (‘S’ in (2)) which depends upon a thickness of an oxide film. According to [4], such films are formed under the impact of current and represent materials close to semiconductors. The film thickness (H) depends upon properties of work material, and in a classical comprehension it is expressed through the energy of discharge (\( A_o \)), Boltzmann constant \( R \) and temperature \( T \):

\[
H = K_H \cdot e^{-A_o/R \cdot T \cdot \tau_H}, \tag{4}
\]

where \( K_H \) – dimension factor taking into account a rate of the film increase depending on material properties.

A limiting thickness of oxide films for nickel-containing alloys amounts to 15-30 \( \mu m \) according to [4], and in titanium materials - up to 50-60 \( \mu m \). Hence, an inter-electrode gap (S) will be close to these values for obtaining a pulse breakdown voltage, even less than 10 V is enough. Oscillography has shown that with such voltages, the appearance of glow discharges is possible, which do not arouse a hole formation. Therefore, a mutual travel of mating surfaces under pressure allows thinning a film up to obtaining local areas with the conductivity during which micro-discharges can be formed [6;7].

The computation through formula (1) allows estimating the depth of a hole which, according to [3], equals:

\[
h = K_h \cdot d_n, \tag{5}
\]

where \( K_h \) – coefficient. According to [3], for steel \( K_h = 0.25-0.35 \). The value ‘\( h \)’ is limited with the allowance (\( Z_o \)) for finishing:

\[
h < Z_o - \delta, \tag{6}
\]

where \( \delta \)– error of a surface after the first stage of finishing. According to [2], this value amounts to 3-4 \( \mu m \). From this, it follows that the allowance for the final stage will be:

\[
Z_o = h + \delta,
\]
and does not exceed 5-6 \( \mu m \).

Through the depth of a hole, it is possible to determine value Rz (Figure 3) upon the dimension of which an anodic constituent of the process has an influence, and the appearance of nano- and microparticles of the material was developed by an electroerosion method in the space between mating surfaces (Figure 4). The degree of their accumulation depends upon the area of mating areas, the speed of contact elements travel and the modes of erosion working.
The analysis of Figure 4 shows that for alloys based on iron and copper, the law of variation in a hole value is close to a linear one, and with the limiting concentration of particles, growth Rz can be considered by constant coefficients K₁ and K₂, taking into account particles conductivity and environment viscosity (for steels K₁ and K₂=1.15-1.16, for copper alloys – 1.25-1.3, aluminum alloys - 1.55-1.6). The existence of treatment products can change not only surface roughness, but also corrosion resistance of parts [9; 10].

The anodic dissolution (Figure 2) contributes to the smoothing of a microsurface in finishing modes of a combined process and allows decreasing an imperfection height by 20-30% which can be taken into account by coefficient K₂=0.7-0.8.

Value Rz₀ obtained without taking into account the influence of particles and an anodic constituent of the combined process (Figure 3) can be computed through the formula similar to that shown in [2;8]:

\[ Rz₀ = \beta \frac{d_n}{l} K_h \]

where \( \beta \) – coefficient of hole covering.

\[ \beta = \frac{d_n}{l}, \]

where \( l \) – distance between neighboring holes. At the finishing stage of the treatment, \( \beta = 0.7-0.8 \).

Taking into account the impact of nano- and micro-particles and also an anodic constituent of the process, the height of micro-imperfections (Rz in Figure 3) can be estimated through the dependence:

\[ Rz = Rz₀ K₁ K₂ = \frac{\beta^2 d_n K_h}{12 \left( K_h^2 + \frac{1}{2} \right)} K₁ K₂. \]

From this it follows that it is possible to find a value of the capacitance of capacitors (C) during the machining with a RC-generator:

\[ C = \left( \frac{R_z}{K₃ U} \right)^3, \]

where \( K₃ \) – coefficient, the values of which are shown in Table 3 and used for the combined treatment.
A minimum value for the rate of mating surfaces travel \( (V \text{ in Figure 2}) \) depends upon an initial profile of contact areas and grows according to imperfections removal as a contact area increases and products of machining begin to impede the deionization of an inter-electrode space. The size \( (L_d) \) of a contact surface along the direction of a travel depends upon a product design, and the rate of the accumulation of particles in an inter-electrode space - upon energy and frequency of pulses. With a certain reserve for a finishing electro-erosion constituent of machining, we can assume that with the limiting fill-up of volume \( V_n \) of a hole room (Figure 2) with products of machining, they must be removed with liquid working medium at the expense of a mutual movement of mating elements in a contact device.

If we assume a form of nano- and micro-particles as a spherical one, then during the filling of space \( V_n \) between electrodes with the concentration \( \varphi \) time \( (\tau_0) \) of a cycle of space purification:

\[
\tau_0 = \frac{V_n \cdot \varphi}{(a + bC)UK_1K_3K_4},
\]

where \( a, b, K_4 - \) coefficients. Here, \( K_4 \) takes into account machining conditions (working medium, a treatment procedure, a sequence frequency of working pulses). \( \varphi \) -characterizes the degree of filling a hole with depth \( h \) by products of machining. For spherical particles, \( \varphi = 0.6-0.7 \). For RC, the procedure of machining numerical values \( a, b, K_4 \) are shown in Table 4:

\[
\begin{array}{c|c|c|c}
\hline
\text{Work material} & \text{Value } K_4 & \text{Combined machining} \\
\hline
\text{Carbon steel} & 0.4-0.45 & 0.25-0.3 \\
\text{Alloyed steel} & 0.3-0.4 & 0.2-0.25 \\
\text{Copper alloys} & 0.7-0.8 & 0.3-0.4 \\
\hline
\end{array}
\]

The period of polarity changing \( (\tau_1) \) for an electro-erosion and electro-chemical constituent of the combined process depends upon time of purification of an inter-electrode space and a height of imperfections of each mating surface before grinding. If these indices are close, then:

\[
\tau_1 = \frac{\tau_0}{2} = \frac{V_n \cdot \varphi}{(a + bC)UK_1K_3K_4}. 
\]

So the rate of contact surfaces movement essential for the removal of machining products can be estimated through the dependence:

\[
V \geq \frac{L_d(a + bC)UK_1K_3K_4}{V_n \cdot \varphi}. 
\]

The pressure of clamping \( (P \text{ in Figure 2}) \) must be controlled according to the value of current between contact surfaces. For the stable procedure of an electroerosion treatment process, it is necessary to have an average current density \( (j) \) not lesser than 0.01 A/mm². In the area of contact surfaces \( (F_k) \), a control parameter (current \( I \)) makes:

\[
I = j \cdot F_k. 
\]

For the electro-erosion and electro-chemical constituent of the combined process at the first stage of finishing, the polarity is equal. Here, an anodic impact is directed mainly to the decrease of a hole depth (hence, to the reduction of the height of micro-imperfections). At the expense of the adjustment
of clamping pressure and the rate of the mutual movement of contact surfaces, the anodic dissolution of projections can be carried out at voltages of a low-voltage source (8 in Figure 2), 3-4 V, which earlier was considered to be unrealizable because of large impedances in an inter-electrode gap with current passing through an oxide film. The combined process offered at low voltage allows clearing short circuits and simplifying considerably the designs of plants for the precision finishing of contact devices.

The final stage of finishing is carried out through anodic dissolution with alternating current with voltage 3-4 V from source 8 (Figure 2). The dimensions of the particles of machining products in finishing modes do not exceed 100-1000 μm, and their capacity is 150-200 times larger than that of the metal removed.

If we assume that the volume of machining products (hydrates, gases and liquid vapors) in the space between holes during their confrontation is equal to 2 Vₘ, then before a final stage of finishing, the volume (Vₘ) of the metal removed from a contact surface close to a metal hole cannot exceed:

\[ V_{m} = \frac{2V_m}{\varphi_1}, \]  

(14)

where \( \varphi_1 \) - ratio of volumes of machining products in a hole to the volume of the metal removed close to a hole (\( \varphi_1 = 150-200 \)).

In the process of micro-surface smoothing (Figure 3), the volumes of holes will decrease and the height of imperfections (R₉) will be reduced up to 20-30 μm (Table 1). It follows from (14) that the rate of anodic dissolution at the end of finishing will be measured by nano-meters in unit time, and a check parameter - duration of a process (\( \tau_f \)) — for both mating surfaces will make:

\[ \tau_f = \frac{\gamma_u \varphi_2 (R_{H} + \delta_{H}) \left[ \varphi_2 (R_{H} + \delta_{H}) + 2R_{H} \right]}{\eta \alpha \chi (U - \Delta U)}, \]  

(15)

where \( \gamma_u \) - density of work material; \( \varphi_2 \) — coefficient taking into account the rate of surface smoothing at an uneven allowance. For the final stage of finishing, \( \varphi_2 = 1.1-1.2 \). \( R_{H} \) - height of imperfections; after the first stage of finishing (according to Table 1, \( R_{H} = 0.8-3.2 \) μm); \( \delta_{H} \) - error at the beginning of the second stage of finishing (0.1-1.0 μm according to Table 1); \( \eta \) - output on current. For very small gaps, according to [4], \( \eta \) is by 10-20% lower than it is shown in recommendations [3]; \( \alpha \) - electro-chemical equivalent of work material (reference data, for example, of those shown in [3]); \( \chi \) - specific conductivity of working medium. If working is carried out in industrial water, then electroconductivity may be chosen according to [3] for the concentration of salts of about 1%, \( U \) - voltage on electrodes. In the case under consideration, \( U = 3-4 \) V, \( \Delta U \) - voltage losses (mainly, ohmic ones in an inter-electrode space). On the basis of [3], [4], at small gaps voltage, losses make \( \Delta U = 1-2.2 \) V. The period of the final stage of finishing can make tens of minutes (Figure 5), whereas the duration of the first stage does not exceed 1-2 min.

During finishing on a mating part with a larger area, there can be formed a projection between an area of machining and an inoperative part of a surface with the value of up to 2-5 μm, which is commensurable with the roughness of a blank (3.2 μm), has a smooth transition (at the expense of the current dispersion during anodic dissolution of the boundary of a finishing area). A projection does not affect the capacity for work of locking equipment, but the narrow boundaries of tolerances (less than 1 μm in Table 1) at the final stage of machining can be a sign of a reject. Therefore, it is expedient under technical conditions regarding a mating unit to point at a permissibility of a local transfer area with a height drop within the limits of 5-10 μm.

6. Conclusion
1. The method for a nonabrasive finishing of mating surfaces in metal locking devices with the formation of contact areas having an error within the limits of 20-100 μm by means of two-stage combined machining is offered.
2. It is shown that at the first stage, without abrasive use, it is possible to obtain a micro-profile by means of an erosion-chemical method where geometrical deviations of mating surfaces are close to the height of microimperfections of the finishing stage in the mechanical refinement. It allows obtaining the imperfection height of a nano-value at the final stage of finishing by means of anodic dissolution which ensures the impermeability of locking equipment operation at high pressure differences, in hostile environment and with a high discharge of working environment.

3. There are developed operating practices taking into account local removals of the material with the allowance at the level of nano- and micro-values which allowed ensuring a required accuracy in mating surfaces without the use of abrasive environment causing a charging of contact areas in the area of finishing.

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