Improving the process of anodic abrasive polishing of small-section channels

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Abstract. The article studies the issues of increasing the quality of the surface and structure of a current-carrying skin layer in the small-section waveguide channels. We offer a promising technique of anodic abrasive polishing, which allows to remove anodic films from a machinable surface, activate and polish microroughnesses. We have developed the flow-chart of anodic abrasive polishing of small-section channels and undertaken a study. The process of anodic abrasive polishing can ensure the high quality of soft materials without impregnation of a machinable surface, as well as the high quality of hard materials with fine finish to Ra 0,04 micrometers keeping the original accuracy and structure of a current-carrying skin layer. We have presented a model and some recommendations how to perform anodic abrasive polishing.

Finishing techniques play a very important role in the context of maintaining the quality of machinery parts: they can be used to finish small-section channels, e.g. rectangular in section 7,2×3,4 mm and others, as well as round in section Ø 4,2÷2,0 mm.

It is known that performance characteristics of products are often determined by the parameters of the quality of the surface layer of parts (especially by surface roughness); for the channels of waveguides they are determined by the structure of a current-carrying skin layer as well [1]. The existing methods of surface machining are divided into mechanical (resurfacing), chemical, physical, electrochemical and combined [2, 3]

The most common are the methods of surface machining by resurfacing (mechanically) with the use of abrasive materials that allow to decrease surface roughness to Ra 0,08-0,2 micrometers. The task of a finishing operation is to remove any defects of previous working (grooves, scratches, small cavities, microasperities, etc.) in order to obtain a smooth surface capable to reflect light well or to decrease electric losses while electromagnetic waves are passing through the channels of the waveguides of antenna-feeder devices [4, 5].

At the time of mechanical polishing coarse irregularities are being removed successively, and at the completion coarse irregularities are removed and a mirrored shiny surface is obtained. Mechanical polishing can influence the structure of the skin layer of a current-conducting surface. While electropolishing microasperities are being removed in the first turn, and a shiny surface can be obtained when there is some considerable macroroughness. It occurs when the entire surface is not subject to the etching effect of an electrolyte. At the time of electrochemical polishing a machinable surface is not almost subject to a thermal and mechanical effect and it does not influence the structure of a current-carrying skin layer significantly.
In the paper [6] on the ground of the analysis of solution products it is concluded that smoothing of microroughnesses of a surface is connected to the exhaustion of chemical activity of an electrolyte in microdepressions of the machinable surface of a part that is an anode at electrochemical polishing.

The other authors [7] note that the process of electrochemical polishing is followed by the formation of passive films on the anodic surface of the workpiece being machined. The film can reach the thickness 0.07÷0.17nm. The work [8] notes that the process of electrochemical polishing may occur if the maximum current is reached, the value of its current density is in the range of 30-300 mA/cm². It is supposed that electrochemical polishing with the planarization of microlief is performed by a film mechanism [9]. Smoothing of roughnesses occurs in consequence of different levels of passivation of bulges and depressions of microroughnesses. According to the theoretical analysis of the undertaken studies, we can conclude that the process of electrochemical polishing can be performed by a diffusive or film mechanism.

In the paper [10] the researchers note that electrochemical properties of a semiconductor oxide film decisively influence the mechanism of electrochemical polishing. The characteristics of this film depend on the composition and nature of an oxide, the composition and properties of an electrolyte being used in the diffuse layer. The dependence on the nature of an oxide is such that some metals are polished only at high current density within the conditions of oxygen release, when higher oxides of a machinable metal are formed, for example, iron and steel, aluminium and its alloys are subject to electrochemical polishing (in phosphoric-chromate or sulfur-phosphoric-chromate electrolytes, nickel in chlorhydric acid or sulphuric acid). Copper and its alloys are polished by this mechanism in phosphorus acid and phosphoric-chromate electrolyte. When performing electrochemical polishing, despite the formation of an oxide film on the machinable surface of a workpiece, during anodic dissolution of a metal it is necessary to make electric lines of force concentrate mainly on microirregularities. It will contribute to the augmentation of electrochemical polishing, at the same time decreasing the removal of metal and the time of machining in order to achieve the required surface roughness. The work [11] highlights that in some processes of electrochemical polishing the determining factor is not smoothing of the surface of a machinable part, but further appearance of microroughnesses due to the nonhomogeneous dissolution of an alloy being machined that is caused by its microstructure.

The electrochemical potentials of anodic dissolution of different metals in the same electrolyte and under the same conditions may be different [12].

Table 1 presents electrochemical potentials of dissolving iron and steels with the content of nickel and other elements in some electrolytes of neutral salts.

| Metal or steel | Current density, A/cm² | Electrolyte composition | Electrochemical potential of dissolution |
|---------------|------------------------|-------------------------|----------------------------------------|
| 1 Iron        | 5                      | 15% Na₂SO₄              | +0.5                                   |
| 2 H18N9T 5ChNM | 5                      | 15% NaCl                | +0.65                                  |
| 3 E1958 5ChNV | (15÷20)%NaNO₃          |                         | +1.15                                  |
|              |                        | 15% NaCl                | +1.7                                   |
|              |                        | (15÷20)%NaNO₃           | 1.7÷2.8                                |

For homogenous dissolution of microroughnesses of a material being machined, it is necessary to choose an electrochemical potential ensuring the uniform dissolution of all the elements in the composition of a machinable material.

While studying a great number of metals it is discovered that the best quality of a surface is obtained with the certain range of potentials (figure 1), (Ea–Eb) is the area of voltammetric characteristics of a metal.

On the area Ea-Eb the current density hardly depends on the potential. In this area the anodic dissolution of a metal is controlled by mass transfer [13]. The maximum current corresponding to this
range of the potentials characterizes the process of the formation on an anode of a passivating film that decelerates the etching effect of an electrolyte and burnishes the metallic surface. The thickness of a passivating film depends on the ratio of the speed of its formation and dissolution in an electrolyte.

![Figure 1. The schematic diagram of the anodic polarization of a metal](image)

As it follows from the graph of anodic curves, the steel Ch18N9T being polarized with the high density anodic current (20-40 A/cm²) in the solution of 15% NaCl at the rate of electrolytes 4 m/s is subject to the anodic dissolution in the active condition at the electrochemical potential $\varphi_a=1.7$ V. When the stream speed is decreased to 1 m/s, the anodic dissolution passes into the transpassive condition at $\varphi_a=3$ V [12]. In view of this, the speed of pumping of an electrolyte may have a great impact on the mechanism of electrochemical polishing in the neutral bath. The mechanism of electrochemical polishing of parts is influenced by original surface roughnesses as well, e.g. the current density on the bulges and depressions in the chloride electrolyte may differ by a factor of five, and in the nitrate electrolyte it may differ by a factor of approximately eight [14].

This difference may become greater if the potential of an anode increases. This difference is measured using the coefficient $K_t = \frac{i_{depr}}{i_{bulg}}$, where $i_{depr}$, $i_{bulg}$ – current density on bulges and depressions.

The increase of the current density on the bulges leads to the higher rate of the dissolution of microirregularities and to the augmentation of smoothing of a surface microprofile. The highest rate of smoothing is noticed while the electrochemical polishing of surface roughnesses with the narrow angle $\alpha$ at the peak of the depressions.

To ensure the reference accuracy and the uniform roughnesses of a surface while polishing small-section channels, it is offered to use a new combined method of anodic abrasive polishing [15] with an elastic abrasive tool that involves reciprocating motion and vibration of an elastic tool in relation to a workpiece. It ensures the pressure of an elastic tool to a machinable surface and simultaneous electrochemical anodic polishing of microroughnesses of a channel surface while supplying an omnipresent electrical or impulsive potential onto a workpiece being machined or a cathode. During anodic abrasive polishing specialists use the tool consisting of two abrasive elastic parts; a cathode is installed between these parts (figure 2).
Figure 2. The model of abrasive anodic polishing of a small-section channel

The outer profiles of the above mentioned elastic parts and a cathode follow the shape of the channel being machined, provided that in both parts along a long axis cavities are performed in the shape of frustum of pyramid, their cross section follows the shape of the outer profile of an elastic tool and these cavities are directed towards each other by their small bases.

The cathode is installed in such a way that the channels are formed among the cathode, the surface being machined and the opposite butt ends of the elastic parts of the tool that provide electrolyte supply to the machinable surface. On the outside surface of the elastic parts of the tool there are two helical grooves to pump the electrolyte. The reciprocating motion of the elastic tool in the small-section channel is performed through the sequential feed of the electrolyte to the symmetric cavities of the elastic tool and with the help of a ram. The cathode integrated with the elastic tool may subject to the vibration from a mechanical drive with the definite frequency $f_u$.

At the elastic anodic abrasive polishing there is a decrease of specific pressure on an elastic abrasive tool. As a result, we have the scheme of sparking-out that ensures significant reduction of surface roughness. Herewith, the ratio of the amount of $S$ shear to the radius $r$ of the blade edge of the abrasive grains $r$ is defined by the frictional factor $f_{fr}$ and it influences the formation of roughnesses due to the plastic deformation of microroughnesses of a material. The paper [17] shows that $R_{max}$ depends on the diameter of V-abrasive, its mortality factor $a$, the coefficient of roughness excursion $\gamma$.

$$R_{max}=0.085B, \ a \ R_{a}=0.25, \ R_{r}=0.021B; \ R_{ai}=\alpha \gamma B.$$  

The limit value of the ratio of shearing intensity $S$ to the radius $r$ of the truncation of the abrasive grain edge, at which the cutting process turns into the process of plastic deformation without the
formation of metal chips, is defined by the index of friction \( f_r \) of the abrasive grain with the material being machined.

The linear rate of electrochemical shearing of a metal layer from microroughnesses may be determined using the following formula:

\[
V = \varepsilon_v \cdot \eta \cdot i \text{ cm/min,}
\]

where \( \varepsilon_v \) – volumetric equivalent weight (mm\(^3\)/A·min); \( \eta \) – metal anode efficiency; \( i \) – current density, A/cm\(^2\).

Current density may be calculated using the formula:

\[
i = \frac{(U - \Delta U) \chi}{\delta_{eg}}.
\]

where \( U \) – electrode voltage, \( V \); \( \chi \) – electrolytic conductivity, cm·O\(^{-1}\); \( \Delta U \) – drop in voltage in cathodic and anodic layers, \( V \); \( \delta_{eg} \) – the value of interelectrode gap, cm.

\[
\Delta U = \varphi_a + \varphi_c.
\]

where \( \varphi_a \), \( \varphi_c \) – potentials on the anode and cathode, \( V \).

The value of the metal layer being sheared using the electrochemical method can be determined using the following formula:

\[
S = i \cdot \eta \cdot \text{iter} = \frac{\varepsilon_v \cdot \eta \cdot (U - \Delta U) \chi \cdot 10^{-2}}{\delta_{eg}}, \text{ cm}
\]

where \( \text{iter} \) – time of the cycle of electrochemical polishing, min; \( 10^{-2} \) – the coefficient of value conversion.

The drop in voltage in near-electrode layers on bulges is considerably less than in depressions (\( \Delta U_{bulg} < \Delta U_{depr} \)) due to the activation of the combs of microroughnesses with an elastic abrasive tool approximately by 10-15 times. It leads to the higher rate of dissolving microroughnesses of the surface being machined compared to microdepressions.

Taking into account the cyclicity of machining, the surface roughness after each cycle of anodic abrasive polishing may be defined as:

\[
R_{an} = R_{an-1} - (1 - n \cdot 10^{-1}) \left[ \frac{\varepsilon_v \cdot \eta \cdot (U - \Delta U_{bulg}) \chi \cdot 10^{-2}}{\delta_{eg}} + \alpha \cdot \gamma \cdot B \right] \cdot \tau
\]

where \( R_{an} \) – roughness of the next cycle, micrometers; \( R_{an-1} \) – roughness of the previous cycle, micrometers; \( n \) – sequence number of the cycle; \( \alpha, \gamma, B \) – the influence of abrasive polishing on the decrease of surface roughness; \( \alpha \) – the coefficient of the change of the diameter of an abrasive after each cycle of abrasion; \( \gamma \) – the coefficient of the change of roughness volume after each \( i^{th} \) cycle of machining, \( B \) – the diameter of an abrasive grain, \( \tau \) – time of the cycle of anodic abrasive polishing.

The time between the cycles \( \tau \) is calculated using the formula [18]:

\[
\tau_{bc} \geq \left( \frac{ZF}{2T} \right)^2 \pi DC_s^2
\]

where \( Z \) – ion charge; \( F \) – Faraday constant, kl/mole\(^{-1}\); \( D \) – the coefficient of ion diffusion of a metal being machined, cm\(^2\)/s; \( C_s \) – ionic concentration on the surface of a resulting workpiece, mole/cm\(^3\).

To calculate \( C_s \), we can use the known dependence [3]:

\[
C_s = \frac{i \cdot \delta_{eg}}{ZF \cdot DB}
\]

Putting the expression (7) into the formula 6 we get the following:

\[
\tau_{bc} \geq \left( \frac{\pi \delta_{eg}^2}{4D} \right)
\]
The duration of the current impulse at anodic abrasive polishing can be calculated according to the formula [19]:

$$\tau_{imp} \leq \frac{\delta (\rho_e + \rho_{gl})}{20k} = \frac{\delta}{20k}$$  \hspace{1cm} (9)

where \( \rho_e \) and \( \rho_{gl} \) – volume resistivity of an electrolyte and gas liquid mixture; \( k \) – coefficient connecting the volume of flash gas with the thickness of gas liquid mixture.

As operating environment one uses the electrolyte that excludes intercrystalline etching of the surface being machined, e.g. 15% NaNO₃. Figure 2 shows the model of the process of anodic abrasive polishing.

In the vessel for polishing 1 the workpiece 2 is installed and the tool for abrasive anodic polishing is put into the port hole being machined. The tool is compound, it consists of two elastic parts 3 with the cathode 4 between them. The outside profiles of the elastic parts 3 and the cathode 4 follow the shape of the port hole being machined. In both elastic parts the symmetric cavities are performed in the shape of frustum of pyramid, their cross-section follows the shape of the outside profile of an elastic tool, these cavities are directed to each other by smaller bases. The cathode 4 is installed with the formation of the channel 5 between the cathode 4 and the surface of the workpiece being machined, and the channels 6 between the butt ends of the cathode and the butt ends of the elastic parts of a tool. To pump the electrolyte, on the outside surface of the elastic parts of a tool helical grooves 7 are made. An electrode is fed into the symmetric cavities of the parts of a tool through the conic stages of the stems 8, in turn under the pressure \( P_1 \) and the opposite pressure \( P_2 \) ensuring the contact of the tool with the surface being machined, then the electrolyte gets into the channels 5 and 6. The anodic dissolution between the cathode and the surface being machined is provided by the voltage from the supply equipment 9 connecting the positive bar to the workpiece 2 being machined, and the negative one 10 – to the cathode 4. Herewith, the removal of the combs of roughnesses on the surface being machined occurs. Resulting anodic and oxide films are removed using the abrasive grains of the elastic parts 3 of the tool performing reciprocating motion with vibrational oscillations from the stems 8.

The removal of the combs of roughnesses on the surface being machined is generally performed by means of anodic dissolution between the cathode of a tool and the surface being machined. The resulting anodic and oxide films are removed from the combs of microroughnesses using the abrasive grains of the abrasive-carrying elastic parts 3 of the tool performing reciprocating motion with simultaneous vibration. These both motions in the process of removing anodic and oxide films render the combs of microroughnesses active, it causes more intensive dissolution compared to the depressions that are covered with passivating films. It causes smoothing of the profile of the surface being machined as well. Machining products (slime, gas and destroyed particles of an abrasive) are scoured by the flow of an electrolyte. While supplying direct or impulse current onto a cathode and a machinable part we can reduce the roughness of a surface to Ra 0,16...0,04 micrometers.

The application of the pulse current with amplitude-time characteristics onto a cathode and a machinable part along the combs of microroughnesses can be defined using the formula:

$$\frac{\partial \varphi}{\partial t} = \int_{0}^{t_\text{imp}} \frac{\partial i}{\partial t} \leq \Delta \varphi_n$$  \hspace{1cm} (10)

The increase and decrease of polarization allow to reduce the roughness of the workpiece being machined to Ra 0,02-0,04 micrometers [16].

In the formula (10) \( \varphi_p \) – the potential of the anode in the process of active anodic dissolution on the combs of microroughnesses and the potential of passivation of the material of the surface being machined on the depressions of the hole microroughnesses respectively; \( i \) – current density; \( t \) – time unit; \( t_\text{imp} \) – duration of current impulse (ms). The potential \( \varphi_p \) is provided during the anodic dissolution through the activation of microroughness combs with the abrasive particles of an elastic tool and the parameters of electric impulse.

During anodic abrasive polishing, thermal and mechanical forces do not influence significantly the surface being machined (the temperature of an electrolyte in the place of machining does not exceed
25°C), it causes higher resistance of the abrasive grains attached to the outside surface of an elastic tool, as well as it decreases abrasive layer wear and increases the operational life of a tool.

The structure of the current-carrying skin layer of a waveguide channel after treatment does not differ from the structure of a parent metal, there is no impregnation or burns, the roughness of the surface being machined is smooth, the operational life of elastic abrasive tools increases tenfold.

Figure 3 shows the graphs of measuring the roughness of the surface of the small-section channels made of the alloys 32NKD at anodic abrasive polishing in the electrolyte 15% NaNO₃ and at electrochemical polishing [20]. It is concluded that the decrease of surface roughness at anodic abrasive polishing occurs more intensely as a result of the removal of anodic films on the combs of microroughnesses.

Using the offered technique of polishing waveguide channels allows to enhance the quality of a surface being machined and the structure of a current-carrying skin-layer. It allows to increase the processing rate one-and-a-half times compared to the existing techniques of electrochemical polishing in a neutral bath.

![Figure 3](image-url)

Figure 3. The dependence of surface roughness Ra on current density
1-Alloy 32NKD, electrolyte 15% NaNO₃ after anodic abrasive polishing.
2- Alloy 32NKD, electrolyte 15% NaNO₃ after electrochemical polishing.

**Conclusion.**

Following on from the theoretical studies of electrochemical polishing, we have:

- offered the technique of anodic abrasive polishing of small-section channels;
- developed the model of the process of anodic abrasive polishing, as well as the circuit schematic of a pilot unit for anodic abrasive polishing of parts and products;
- presented the results of the experimental studies of anodic abrasive polishing; these results confirm the efficiency of the offered technique of decreasing surface roughness keeping the original accuracy of small-section channels.

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