The study of the light section canal anodic-abrasive polishing mechanism

V I Trifanov, M G Melkozerov, O A Sukhanova, I V Trifanov and D M Mednikov

Reshetnev Siberian State University of Science and Technology, 31 Krasnoyarsky Rabochy Av., Krasnoyarsk, 660037, Russia
E-mail: sibgau-ucks@mail.ru

Abstract. The development of electronic technology, waveguide transmission lines of electromagnetic energy, as well as precision engineering require the development of polishing technologies. One of these technologies is the method of anodic abrasive polishing (AAP). The causal diagram of the influence of technological parameters on the output characteristics of AAP is presented, as well as the model of the process and the analysis of the mechanism of anodic abrasive polishing at the longitudinal vibration contact with the treated surface and the impact of the pulse current density used for electrochemical polishing of micro-irregularities with the help of a cathode integrated with an elastic abrasive tool.

The development of laser technology, the transmission line of electromagnetic energy of the EHF-range and precision engineering place high demands on the surface treatment of metal parts (Ra 0.16-0.005 µm).

To reduce the surface roughness of the canals of light section tubes, an anodic-abrasive polishing (AAP) method can be applied [1,2]. In order to select rational modes of AAP, one should consider the influence of the parameters of the combined process of abrasive effect on the surface quality of the canals of light section, as well as the electrochemical parameters of anodic dissolution.

Figure 1 shows a diagram of the effect of the parameters of abrasive polishing combined with an electrochemical process on the quality of the layer surface and the output parameters of AAP.

In AAP the force of the abrasive effect of the bonded abrasive is used, and the force is directed tangentially to the surface being treated and makes an angle close to 90° with the normal. Under the abrasive effect on the micro-irregularity of the surface being processed, the movement of the elastic abrasive tool (EAT) can be carried out by the vibrocontact method. Research has established [3] that the amount of roughness of the treated surface Ra is largely influenced by the grit size of the abrasive and the working pressure P from the side of the EAT. The abrasive grains of the EAT slide over the surface being treated with a very low coefficient of friction due to the influence of the lubricating properties of the electrolyte and the small rake angle α=10-40°. At the same time, the influence of microgeometry and the energy of the surface layer being processed are also manifested [4].
Figure 1. The causal diagram of the influence of technological parameters on the output characteristics of AAP.
The contact can be considered as the result of reinforcement of the engagement and deformation of the inter-penetrating roughness and asperities of two mating surfaces. With a relative longitudinal vibration displacement of the EAT with amplitude $A$, frequency $\omega$, and pressing force $P_h$, elastoplastic states appear at the microcontacts of the roughness of the processed surface of the light section canal and an energy field appears. The energy field is caused not only by the energy impact of the interaction between two micro-irregularities, but also due to the concentration of electric charge on the activated microprotrusions of the treated surface when a voltage of an external electric field is applied during AAP. The potential for microcavities is reduced due to film formation.

Two types of effects: mechano-abrasive and electrochemical, can ensure the preservation of the initial accuracy and stable microprofile of the processed surface of the canal of light section due to selective alignment of the micro-irregularity.

Reducing the contact force of the abrasive grain with asperities due to liquid and oxide films, as well as aligning the peaks of the asperities can significantly reduce friction and microcutting forces with the abrasive grains of the treated surface, however, the impact of pulsed electric current and electrolyte pumping will allow localizing the process of levelling the asperities due to anodic dissolution within dimensional tolerance while maintaining the original accuracy of the canal of light section.

The scheme of the contact interaction of a single abrasive and the canal of the EAT with the asperities of the treated surface is shown in figure 2. With AAP, there is no impact interaction of the abrasive particles with the treated surface. In this regard, the destruction of abrasive particles is insignificant and the general nature of the contact interaction of abrasive particles with the treated surface is preserved.

In the case of AAP, a single grain contact circuit with the surface to be treated was selected, similar to the grinding grain pattern developed by E.N. Maslov [5]. We assume that microprotrusions M perform the role of independent cutting elements, and the top of the grain is approximated by a radius $r_i$. With an increase in the penetration depth $h$ of the top of the abrasive grain into the metal with a cutting angle $\beta < 180^\circ$, a transition from plastic deformation to microcutting occurs. In this case, the normal force $P$ and the friction force $F_f$ will act on the abrasive grain. These forces are applied to the point A in the middle of the arc of grain contact with the processed micro-irregularity.

The force $P_y$, pressing the abrasive grain to the treated surface, as well as $P_x$, which produces microcutting, can be found by projecting the normal force $P$ acting on the abrasive and friction force $F_f$ on the direction of the x and y axes. After the transformations $P_y$ and $P_x$ can be represented as:

$$P_y = P (\sin \alpha + f \cos \alpha)$$
$$P_x = P (\cos \alpha - f \sin \alpha)$$

Then the normal force $P$ and the force of cutting $P_x$ can be determined as:

$$P = \frac{P_p}{\sin \alpha + f \cos \alpha}$$
$$P_x = \frac{P_p (\cot \alpha - 1)}{1 + f \cos \alpha}$$

where $\alpha$ is the rake angle at the point of contact K of the abrasive grain with the micro-irregularity of the metal surface; $f$ – the coefficient of sliding friction of the abrasive grain on the treated surface; $P_p$ – the pressing force of the grain of abrasive.

The coefficient of sliding friction of the abrasive can be determined by taking into account the ratio proposed in the work of I.V. Kragelsky [6]:

$$f = c \cdot \frac{h_p}{r_i}$$
where $c$ is the coefficient taking into account the effect of contact vibration, film formation on the processed micro-irregularities and the lubricating properties of the electrolyte on friction; $r_i$ is the radius of rounding of the top of the grain; $h_i$ is the depth of abrasive introduction.

Figure 2. Scheme of the contact interaction of a single abrasive and the EAT cathode with the micro-irregularities of the treated surface: 1 is the micro-irregularity of the treated surface; 2 is an abrasive grain of the EAT; 3 is the cathode instrument; 4 is for electric field lines; $\alpha$ and $\beta$ are rake angle and cutting angle at the point of contact $K$; $r_i$ is the radius of the rounding of the top of the grain; $\delta_{\text{EAT}}$ is the value of the interelectrode gap; $h$ is the depth of penetration of the top of the abrasive grain; $P_n$ is the pressing force of the abrasive, $F_r$ is the friction force, $P$ is the normal force acting on the abrasive grain; $A$, $\omega$ is the amplitude and frequency of vibration oscillations of the EAT; $V_u$ is the linear velocity of movement of the EAT.

The repeated use of abrasive leads to rounding of sharp peaks and angles, as well as a change in the microrelief of the surfaces of abrasive grains, which leads to a change in the cutting ability of the aggregate of abrasive particles as a whole, therefore, $r_i$ must be taken into account when calculating $f_{mp}$ in APP.

The resulting cutting force $P_p$ on the processed surface can be calculated by the formula:

$$P_p = P_n S_i f = P_n S_i c \frac{h_i}{r_i} H$$

(4)
where $P_a$ is the external pressure on the abrasive particles; $S$ is the area of EAT with an abrasive-bearing material in contact with the treated surface.

The power of abrasive cutting $N_{cut}$ is estimated by the formula:

$$N_{cut} = M_{cut} \cdot \omega \quad (5)$$

where $\omega$ is the frequency of longitudinal vibrations of the EIA, 1/s; $M_{cut}$ is the moment of cutting, N·m.

$$M_{cut} = P_{cut} \cdot B \cdot 0,5 = P_a \cdot 0,5B \cdot S_c \cdot c \cdot \frac{h_c}{r_i} \quad (6)$$

where $B$ is the thickness of the EAT, m.

It is determined that an increase in pressure $P$ in the range of $0.2 \div 1.0$ MPa raises $Ra$ in $1.2 \div 1.4$ times, which is probably due to an increase in thickness, cut off by a single grain of the layer and an increase in the work of cutting. The radius of rounding of the cutting edge of the abrasive grain has a certain role on $Ra$. It is established that the limiting values of the ratio of the thickness of the slice to the radius of rounding of the cutting edge of an abrasive grain is determined by the coefficient of friction $f_{fr}$ of the abrasive grain with the processed surface [7]. The coefficient of friction can vary within $f_{fr} = 0.1 - 0.3$. Therefore, it is possible to reduce the surface roughness by reducing the friction coefficient of the abrasive grain with the processed material, which can be implemented in AAP, due to the fact that the abrasive method requires removing the anode films from the micro-irregularities.

Studies have shown that after vibrocontact polishing with lodgments with variable stiffness, deviations from the geometrical accuracy of the turbine blade feather profile were no more than 0.05 mm, and the charging intensity does not exceed 0.5% [3]. This is due to the fact that during the abrasive treatment a part of abrasive grains is destroyed, the particles roll freely and some of the grains can be fixed in the defects of the treated surface [8]. In the case of AAP, the process can be carried out with less effort on the EAT, mainly to remove the passivating films on ridges of micro-irregularities.

For finishing polishing an abrasive from 0,01-0,3 microns is mainly used (ultra micro powders are used). A multistage process of preliminary, finishing and fine finishing is also used. Polishing using fine-grained abrasive powder materials can be represented as a combination of processes: mechanical, adsorption, adhesive, wetting and oxidation of the surface layer [9].

The use of nano-dispersed tribochemical active abrasive materials changes the process of finishing polishing with the occurrence of chemical transformations and has a significant advantage over the known abrasive methods: it allows reducing the number of finishing operations with obtaining surface roughness with $Ra$ 0.005 microns. From the point of view of solid mechanics, polishing can be attributed to non-slip friction processes. This is the basis of the AAP mechanism.

When an abrasive tool interacts with the treated surface, its single protrusion produces elastic and plastic deformation of the material [9]. After contact with the surface, elastic deformation begins, passing as it deepens into plastic. The depth of penetration of the grain depends on the kinetic energy of the movement in the direction normal to the surface [10]. The movement of grain in the direction parallel to the processed surface is accompanied by micro-cutting of the part.

The amount of material removed in the process of abrasive treatment consists of the volumes of chips that were shredded and destroyed as a result of polydeformation, which depends on the volume of plastically and elastically deformed material under the action of a single grain, as well as on the number of these impacts per unit of surface per unit of time. The achievable roughness is determined by the transverse and longitudinal sections of scratches applied by single grains to the surface. The model of interaction of a single grain with an elastoplastic half-space can be used to determine the normal $P_N$ and tangential $P_T$ of cutting forces.

$$P_N = \delta_{sh} \cdot r_i^2 \cdot f_{fr} \quad P_T = \delta_{pen} \cdot r_i^2 \cdot f_N \quad (7)$$
where $\delta_{sh}$ is the shear yield strength of the material; $r_i$ is the radius of rounding of the tops of the irregularities of the abrasive grain; $f_T$ and $f_N$ are dimensionless coefficients of forces characterizing the conditions of scratching of the material; $P_N$ and $P_T$ are tangential and normal cutting forces on a single grain [11].

The yield strength of various materials with elastoplastic properties varies differently in the scratch depth. For example, copper and stainless steel almost do not change their properties, however, after multilateral deformation of pipes of light section, the yield strength may change.

The interaction of the cutting microrelief of the EAT with the processed surface depends on many factors (the depth of introduction of the abrasive grains, the number of grains in contact, the radius of the grain tops).

Elastic abrasive tools allow to provide less surface roughness than rigid ones for the surface may be smoother when a larger number of elementary cutting profiles are involved in its formation. Elastic tools have significantly larger areas of contact with the treated surface than rigid ones, therefore their use is preferable for AAP.

For AAP, an elastic abrasive tool is used, in which a cathode is installed for anodic dissolution of micro-irregularities [2] that can reduce the cutting forces on the part of abrasive grains and process thin-walled canals of light section.

When vibrocontacting the EAT in the process of AAP, the roughness of the processed surface can be influenced by the amplitude and frequency of vibrations, grain size, density of distribution of grains over the abrasive surface, physical and electrochemical properties of the processed material, as well as the mechanism of anodic dissolution of micro-irregularities [12]. The influence of electrolyte is associated not only with the intensity of anodic dissolution of micro-irregularities and passivation of microdepressions, but also with the reduction of friction losses when exposed to abrasive particles when they are vibrated moving along the surface of the processed canal. Figure 2 shows the components of the forces acting on the surface of the part with an abrasive grain, as well as the principles of electrochemical polishing (ECP). The AAP process can provide the roughness of $Ra$ 0.2–0.04 $\mu$m without deforming the treated surface with a low temperature effect with less effort on the EAT.

When AAP, the treatment process should be carried out with preservation of the initial accuracy of the light section canal. The AAP process can be affected by the physicomechanical and electrochemical properties of the processed material: microhardness, microstrength (tear resistance), modulus of elasticity, yield strength of the processed material, shear modulus, Poisson's ratio, material density, electrochemical equivalent, metal current output of the material processed by electrochemical method, the uniformity of anodic polishing associated with the electrochemical properties and structure of the processed material.

When calculating the technological parameters of abrasive processing with an EAT, it is necessary to apply a coefficient $\lambda$ taking into account the influence of the physicochemical properties of the processed material [9], for example, when determining the total polishing time $T_0$ according to the formula:

$$T_0 = n_i \cdot \gamma \left( \frac{\lambda \cdot R_{d_0}}{R_{d_n}} \right)^{1/n_i}$$  \hspace{1cm} (8)

where $n_i$ is the number of impacts of the interaction of abrasive grains with microroughness per unit of time; $\lambda$ is the coefficient taking into account the physicochemical properties of the processed material, $R_{a_0}$, $R_{a_n}$ are initial and final roughness of the treated surface; $\gamma$ is the coefficient taking into account the conditions of abrasive polishing:

$$\gamma = \frac{K\beta}{\alpha_r \text{мм}}\text{мин}^{-1},$$  \hspace{1cm} (9)
where $\alpha$, is the coefficient taking into account changes in the radius of the abrasive after each treatment cycle; $\beta$ is the coefficient of change of the roughness value after the $i$-th processing cycle; $K$ is the coefficient depending on the geometric characteristics of the processed surface and the AAP scheme;

$$K = K_1 + K_2 + K_3$$  \hspace{1cm} (10)

where $K_1$ is the shape factor of the treated surface; $K_2$ is the coefficient taking into account the depth of the defective layer of the treated surface; $K_3$ is the coefficient depending on the technological parameters of the EAT of the adopted mechanism of the processing process, $K_3 \approx 3,73 \div 4$.

The number of impacts of interaction of abrasive grains with micro-irregularities during polishing is determined by the formula [9]:

$$n_i = 2,31 \cdot \ln \frac{R_{z_i}}{R_{z_n}}$$  \hspace{1cm} (11)

where $R_{z_n}, R_{z_n}$ are the initial and final values of the roughness of the treated surface, determined by the established requirements.

Formula (12) shows that $n$ depends on the initial and final roughness of the treated surface.

$$K_{ep} = \gamma \cdot \lambda$$  \hspace{1cm} (12)

Where $K_{ep}$ is the coefficient depending on the properties of elastic-plastic deformation of the processed material.

The life period $T_{lp}$ of elastic abrasive tool is determined by the formula:

$$T_{lp} = \frac{60 \cdot V_n}{Q}$$  \hspace{1cm} (13)

where $V_n$ is the volume of the steam space of the abrasive tool, mm$^3$; $Q$ is efficiency in mm$^3$/min; $V_n$ depends on the area of the treated canal surface (width $a$ and length $L$), as well as on the diameter of the abrasive grain $D$ and the technological density of the abrasive grains $\rho$ on the surface of the elastic tool.

The coefficient $\lambda$ can be determined by the formula of one of the dependencies [9]:

$$\lambda = \left(\lambda_{M_s}, \lambda_R, \lambda_{EG}\right)^{1/3}$$  \hspace{1cm} (14)

where $E$ is the modulus of elasticity; $G$ is the shear modulus; $R$ is the microstrength; $M_s$ is the microhardness.

The removal of material from a unit of area during anodic-abrasive polishing can be determined by the formula [10]:

$$Q = (Q_c + Q_{pl})T_0 \cdot n_i + Q_{AH}$$  \hspace{1cm} (15)

where $n_i$ is the number of impacts of the interaction of grains of abrasive with microroughness per unit of time, 1/s; $Q_c$ is the volume of material displaced in the form of chips in one blow; $Q_{pl}$ is the volume of material destroyed as a result of plastic deformation per one blow, mm$^3$; $Q_{AH}$ is the additional volume of material removed by the anodic electrochemical dissolution of micro-irregularities in the combined AAP process.

$$Q_{AH} = \left(E_v / \eta \cdot i \right) t_p$$  \hspace{1cm} (16)
where $E_v$ is the volume electrochemical equivalent ($\text{mm}^3/\text{A min}$), $\eta$ is the metal anode current yield in the treated electricity, $i$ is the current density, $\text{A/cm}^2$, $t_p$ is the time of anodic dissolution, min.

$$i = \left[ U - (\varphi_c + \varphi_a) \right] \frac{\chi}{\delta_{eg}},$$

(17)

where $U$ is the voltage at the electrodes, $\varphi_c$ and $\varphi_a$ are the electric potentials at the cathode and the anode, $\delta_{eg}$ is the size of the inter-electric gap, $\chi$ is specific conductivity of electrolyte, cm$^2$Ω$^{-1}$ [12].

The removal of material $Q_A$ per unit of time ($\text{m}^3/\text{s}$) due to the impact of a vibrating abrasive-bearing elastic tool can be calculated by the formula:

$$Q_A = n_i \cdot K_z \cdot Q_c = A \cdot \omega \cdot W \cdot L \cdot K_z Q_c,$$

(18)

where $n_i$ is the number of impacts of abrasive granules in micro-irregularity, $1/s$; $Q_c$ is the amount of the metal removed when exposed to one abrasive grain, $\text{m}^3$; $K_z$ is a coefficient taking into account the number of impacts in micro-irregularity; $A$ is the amplitude and frequency of oscillation of the EAT; $W$ is the density of distribution of abrasive grains over the surface of an elastic tool, $1/\text{m}^2$; $L$ is the length of the treated surface, m.

The amount of metal removed by a vibrating abrasive-bearing elastic instrument during processing $T$ is calculated by the formula:

$$Q_a = Q \cdot T,$$

(19)

The arithmetic average deviation of the profile of the established roughness of the treated surface after $n_y$ cycles of abrasive processing can be determined:

$$R_{\text{at inst}} = K_{ep} \left( \frac{h_{\text{max}}}{W \cdot A} \right)^{1/2},$$

(20)

where $h_{\text{max}}$ is the maximum depth of penetration of the grain of the elastic instrument into the treated surface, m; $W$ is the density of distribution of abrasive grains over the treated surface, $1/\text{m}^2$; $K_{ep}$ is a coefficient depending on the properties of elastoplastic deformation of the metal.

The maximum depth of introduction of the abrasive particle during AAP is proposed to be calculated by the formula:

$$h_{\text{max}} = (A \omega + V_t) 2r \cdot \sin \alpha \sqrt{\frac{mW}{3K_R \cdot c \cdot \delta_s \cdot A}},$$

(21)

where $V_t$ is the speed of movement of the EAT; $m_e$ is the mass of EAT; $r$ is the radius of rounding of the abrasive particle; $K_R$ is a coefficient taking into account the influence of the surface roughness of the part; $\delta_s$ is yield strength of the part material; $c$ is a coefficient taking into account the influence of roughness on the surface of the part; $\alpha$ is the rake angle.

The average depth of penetration of the grain of an elastic instrument $h_a$ into the processed surface can be estimated by the formula:
where \( N_c \) is a power of abrasive cutting of micro-irregularities; \( H_v \) is hardness of the treated surface by Vickers.

The roughness of the treated surface during an abrasive vibration contact with the surface can be determined by the formula:

\[
R_{a_i} = R_{a_{iw}} - K_z \cdot \frac{R_{a_{iw}}}{R_{a_{iw}}} \cdot \sin \beta \cdot \frac{\delta_{uss}}{\delta_{usm}} \cdot \left( \frac{2A \cdot \omega \cdot WL \cdot V_{cut} \cdot m_i}{\delta_{uss} \pi r} \right)^{1/2} \cdot T_c
\]  

where \( R_{a_{iw}}, R_{a} \) are the initial height of the irregularities of the workpiece and the elastic abrasive tool; \( K_z \) is a coefficient of abrasive grit; \( V_{cut}, \beta \) are speed and angle of cutting of micro-irregularity; \( \delta_{uss}, \delta_{usm} \) are ultimate strength of the abrasive particle and material; \( m_i \) is the mass of instrument; \( r \) is the radius of rounding of the abrasive; \( T_c \) is the processing cycle time.

Taking into account the formulas (17) and (24), we obtain an expression for calculating the roughness of the treated surface obtained as a result of the AAP during vibrocontact polishing:

\[
R_{a} = R_{a_{iw}} \cdot \frac{1}{(1 - n \cdot 10^{-2})^2} \left( \frac{E_x(U - \Delta U_k)10^{-2}}{\delta_{uss}} \right) \tau_{ce} + K_z \cdot \frac{R_{a_{iw}}}{R_{a}} \cdot \sin \beta \cdot \frac{\delta_{uss}}{\delta_{usm}} \cdot \left( \frac{2A \cdot \omega \cdot WL \cdot V_{cut} \cdot m_i}{\delta_{uss} \pi r} \right)^{1/2} \cdot T_c
\]

where \( T_{u} \) is the duration of one AAP cycle.

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

where \( \varphi_c \) and \( \varphi_a \) are the electric potentials at the cathode and the anode.

The duration of the pulse of electric current with pulsed anodic dissolution of asperities is determined by the formula [13]:

\[
\tau_{pol} \leq \frac{\delta_{eg} (\rho_c + \rho_g)}{2UKg}
\]

where \( \rho_c \) and \( \rho_g \) are the resistivity of the electrolyte and gas-liquid mixture; \( K_g \) is the coefficient connecting the volume of emitted gas with the thickness of the gas-liquid mixture. Anodic dissolution of micro-irregularities during AAP can be carried out in passivating electrolyte solutions of neutral salts (NaNO\(_3\), Na\(_2\)SO\(_4\), NaNO\(_2\) and others) of the corresponding concentration (7 ÷ 15%).

The time between pulses of electric current [11] can be calculated by the formula:

\[
\tau_{bp} \geq \frac{\pi \delta_{eg}^2}{4DU}
\]

where \( D_U \) is the diffusion coefficient of the ions of the treated metal, cm\(^2\)/s.

The cycle time of the electrochemical treatment \( \tau_{ce} \) can be represented by the expression:

\[
\tau_{ce} = \tau_{pol} + \tau_{bp} \Rightarrow \tau_{ce} = \sum_{0}^{T_c} \tau_{pol} + \tau_{bp} = T_c
\]
One cycle of anodic-abrasive polishing $\tau_{ca}$ is equal to the sum of the current time $\tau_{pu}$ and pauses $\tau_{pa}$ used for the electrochemical anodic dissolution of micro-irregularities of the treated surface. The electrical power spent on the removal of micro-irregularities by anodic dissolution with the pulse current while processing during the time $T_c$ can be determined by the formula:

$$
N_A = \int_0^{\tau_c} i(t)U(t)dt
$$

where $i(t)$ and $U(t)$ are current density pulse and voltage at the cathode and anode during the AAP cycle.

Pulsed modes of electrochemical processing increase the localization of the anodic dissolution of micro-irregularities, improve the surface quality as a result of discretization of the process of anodic dissolution and relaxation of the properties of the interelectrode medium. Reducing the temperature of the anode reduces the micro-irregularities height and the amount of allowance required to achieve a given roughness value compared to an uncooled electrode, and also eliminates etchings at the grain boundaries, the treated surface [12] with rationally selected pulse duration and amplitude density of electric current. Maintaining the active and passive state on the micro-irregularities and cavities is possible by abrasive exposure and removal of passivating films from the microprotrusions of the treated surface. The microlocal distribution of temperature and electrolyte properties, amplitude-time parameters of current density, active and passive state on microprotrusions and microcavities of the treated surface contribute to the alignment of the microrelief and improve the surface quality in the AAP process.

**Conclusion**

The mechanism of the combined process of anodic-abrasive polishing of light section canals is presented. It consists in electrochemical polishing of micro-irregularities with pulsed current during vibrocontact abrasive interaction of an elastic tool with the surface. The cause-effect relationship of the influence of technological parameters on the output characteristics of AAP has been established. A formula is presented for evaluating the surface roughness after AAP, taking into account the temporal parameters of electrochemical anodic polishing of micro-irregularities with pulsed current and their vibrocontact interaction with an elastic abrasive bearing tool.

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