Review of previous Russian studies in the abrasive flow machining

V A Levko¹, O V Litovka, D I Savin and N S Terjaev
Reshetnev Siberian State University of Science and Technology, 31, Krasnoyarsky Rabochy Av., Krasnoyarsk, 660037, Russian Federation

¹E-mail: levkosaa@mail.ru

Abstract. Abrasive flow machining (abrasive flow machining (AFM)) is increasingly used worldwide. It is used for finishing and removing surface stresses in parts, the finishing machining of which using traditional methods is difficult. By now there are a large number of publications on this topic. A special interest are the articles in which previous works on various aspects of this technology are systematized. Due to a number of reasons, there are no publications from the scientific periodicals of Russia. This article presents a review of the works of Russian researchers in modelling the machining process by abrasive flow. They are aimed at modelling the rheological characteristics of the medium and contact interactions in processing. Particular attention is paid to the machining of an abrasive flow with an aligning device, as well as parts from powder molybdenum. The purpose of this article is to acquaint the wide range of readers with the works of Russian studies in the treatment of the abrasive flow of high viscosity medium.

1. Introduction
The modern level of industrial production led to the widespread use of parts with a complex geometric shape. As a rule, high-alloyed steel, titanium alloys, cobalt, nickel, chromium and molybdenum are used as materials. The surface layer of such parts makes high requirements for the quality of the surface layer, but their finishing processing is difficult in traditional ways.

Therefore, as such a finishing operation, such an unconventional finish-treatment method is becoming increasingly used as treatment with an abrasive stream [1].

The basis of AFM underlies the flow in the processed part under the high pressure of the viscoelastic material filled with fine abrasive particles. The stream of abrasive material (medium) takes the shape of the channel being processed and has a compressive pressure on the surface being processed, providing abrasive contact [2]. To apply this technology in the finishing processing of specific parts, it is necessary to carry out a large amount of experimental studies. This is due to the fact that by the present time the generally accepted theoretical foundations of the machining process by the abrasive flow is not created. With abrasive contact, there is a number of physical phenomena that affect the quality and performance of AFM.

To date, a large amount of experimental and theoretical studies in this area has been carried out in the world. The systematization of such works is presented in the critical review of past studies and achievements in the process of finishing by abrasive flow [3]. This work caused great interest among
readers. However, it does not consider publications under the subject matter in the Russian scientific periodical.

The first open publication in this area in the USSR appeared in 1980 [4]. Since then, in 40 years, a number of patents and scientific articles have appeared in Russia. However, almost all of these works are hard to reach for English-speaking readers. The main reason is that practically all articles are published in Russian. The second reason is that in Russia the machining process with an abrasive flow is more known as abrasive-extrusion processing. This name is used as a keyword in most works, including translated into English. The purpose of this article is an addition to the review [3] analysis of Russian authors whose works were published in leading scientific journals of Russia.

2. Review of published works on modelling the machining by abrasive flow in Russia

Of the four types of machining by abrasive flow in Russia, bidirectional treatment with abrasive stream (Bidirectional AFM) received the greatest distribution. In the Soviet Union, 15 patents were recorded on the device for processing with an abrasive flow, 10 patents on methods for machining by an abrasive flow and 2 patents for the composition of the medium. As a polymer base of medium, synthetic silicone rubber SCT is used [5]. Environments based on this rubber belong to high viscosity environments.

The first publications were devoted to the development of recommendations for the processing of specific details. The basis of the recommendation was the resulting empirical dependencies that bind the pressure of the medium, the grit and the volume of the abrasive medium with the roughness of the treated surface Ra and the removal of the material [6], as well as the change in the stress state of the surface layer [7]. The empirical dependences of the AFM process made it possible to ensure the accuracy of the flow of fuel components through the channel channels [8], as well as the basis of the finishing technology of the profile holes [9]. Recommendations on the choice of equipment, the composition of the medium and processing parameters are proposed [10].

The critical analysis of the current state of this technology has shown that the absence of the theoretical foundations of the process built on the basis of generally accepted representations in the field of tribology and rheology does not allow to assess the boundaries of the applicability of the method from a scientific point of view [11].

2.1. Rheological properties of the work environment

To simulate the stream of the medium during machining by the abrasive flow, it is necessary to know the numerical values of the coefficients characterizing its rheological properties.

The technique of experimental determination of viscosity coefficients, elasticity and plasticity of the AFM medium [12] was proposed. It is based on the experimental determination of the numerical values of the maximum flow rate of the $\omega_{\text{max}}$ medium and the pressure drop $\Delta P$ on the section of the cylindrical channel $L$ and diameter $d$. The device for the study of viscous and plastic properties of the medium is shown in figure 1. The following is described in the paper and a device and a device to determine the numerical values of the Young $E$ module and the Poisson ratio $\mu$ of the high viscosity medium for machining by the abrasive flow [12].

The experimentally numerical values of the maximum flow rate of the medium and the calculated values of the effective viscosity of the medium are used to determine the values of the sliding velocity $\gamma$ of the medium rate. Further, using known formulas for the rheology of viscoelastic liquids, the values of tangent stresses $\tau$ and normal stresses $\sigma$, arising in the medium flow in the circular channel of the constant cross section were calculated [13].
According to the [11] procedure for the shear flow of the medium filled with an abrasive value of 320 μm, at a pressure $P = 6$ MPa in the cylindrical channel $R = 0.0125$ m radius and length $L = 0.07$ m the maximum flow rate of $0.0204 \, m/s$ is determined, the value of an effective viscosity of $36900 \, \text{Pa} \, \text{s}$ was obtained. Next, the rate of shear $\dot{\gamma} = 7.68 \, \text{c}^1$, the value of tangent stresses $\tau = 283331 \, \text{Pa}$, the size of normal voltages $\sigma = 250100 \, \text{Pa}$, the value of the components of the cutting forces $F_a = 2.28 \, \text{H}$ and $F_r = 2.0 \, \text{H}$ [13] were calculated.

To study the effect of the shape of the processable channel, visual studies of the abrasive flow in 28 channels were carried out. To perform them, a technique and a device has been developed, which allows you to fix the stream of medium through a window of organic glass with a thickness of 20 mm [14]. Before visual studies on the surface of the medium placed in the device, a rectangular mesh with a size of 15x15 mm and a depth of up to 2 mm, which was filled with a white electrocorundum F70, was applied by template. A white grid has a good contrast with the surface of the medium, which ensured the desired image contrast. During the studies, the degree of influence of the shape of the processed channel and local resistances on the features of the flow is established. The features of the flow are shown in the form of a series of photographs of the flow for each sample [14].

So, for the flow in the channel (figure 2), the displacement of the stream of medium 4 is characterized from the central axis of the channel. At the same time, at the entrance to the channel, there are not two, but three zones of stagnation 2. Two at the entrance to the canal and one before the partition. Over the partition, the flow separation from the wall of the channel being processed is
observed. Due to the effect of elastic recovery, there is a gradual filling of the entire volume of the channel under study, including for the partition. After filling this section of the channel, the medium in it occurs a stagnant zone. The main part of the flow slides along the border of this zone. Only the surface of the partition is processed, which is parallel to the main stream [14].

When analysing the movement of individual abrasive grains in the medium stream, it is established that they are moved along the current lines. With the steady flow, the distance between adjacent grains does not change. Thus, the assumption of an elastic chain formation in the stream is confirmed. It has been established that the grain in contact with the treated surface performs a rotational motion in the stream [14].

To simulate AFM channels of large length, a model of the flow of a viscoelastic medium filled with abrasive particles is proposed. Observed experimentally in the current line, the set of abrasive grains is presented as a chain consisting of sequentially connected identical elements. Each element is deformed regardless of the rest, and the continuity of the chain is ensured by the compound of the segments of the viscoelastic medium in the balls that simulate abrasive particles. Processing conditions are determined by the stress-strain state of the medium. The magnitude of the deformation depends on the flow rate gradient on the channel wall. It was revealed that with the steady flow, the ratio between normal and tangent stresses is stored along the entire length of the channel being processed [15].

To study the change in the flow pressure of the medium along the length of the channel being processed, a diagram is applied with a pressure registration with four sensors. The results of the study showed that the change in pressure along the length of the channel with the steady flow is insignificant and practically occurs simultaneously along the entire length of the channel [16].

In the study of the medium composition effect on the processing modes by the abrasive flow, it is established that at present, the medium is filled with an abrasive of one grain. In such media, during deformation, abrasive grains form linear chains moving only in their current lines along the entire length of the channel being processed. In this case, with the steady flow mode, the elastic voltage occurs between the current lines with a different gradient of the flow rate and on the surface of the channel being processed [17].

It is proposed to apply media filled with abrasive grains of several grain. They form a different spatial structure. In this case, larger grains play the role of centres around which more numerous grains of smaller sizes are grouped. In this case, abrasive balls occur in the medium, and the resulting abrasive linear chains have a smaller length. In this case, the number of abrasive chains increases. The dependence of the percentage in the medium of each abrasive grain is proposed depending on its value. Such environments were called polydisperse media [17].

2.2. Contact interactions when machining abrasive flow
One of the first in Russia was the experience of describing the contact interactions of abrasive grain with a treated surface based on the contact form of micro-grain microedge during microcutting. Contact options with a sharp cone, sphere, cone with a truncated vertex, a cone with a rounded vertex are considered. It is noted that the obtained formulas give only qualitative agreement with experimental data [18]. The creation of a model of motion of the abrasive grain at AFM will allow to calculate the intensity of the wear of the material at various combinations of all factors [19].

The description of contact processes at AFM from the point of view of tribology made it possible to attribute them to the processes of external friction of a rough and wavy body (billet) with a viscoelastic body (medium). At the same time, the abrasive grain itself in the stream of the medium is experiencing plastic contact. The microasperity of the treated surface at various levels of contact may experience elastic, elastoplastic, plastic deformations, or the microcutting process will be carried out [20]. For all types of contact, the formulas for calculating the actual area of contact of micron of abrasive grain and the treated surface are proposed. On their basis, the equations were proposed to determine the volume of the material being removed and the roughness of the treated surface [21].
When studying the energy processes in the cutting zone at AFM, the empirical dependence of the change in the temperature of the medium during treatment [22] is defined. The direct dependence of the thermal conductivity coefficients and the temperature of the medium is established on the degree of its filling with abrasive grains [23].

3. Overview of published works on the development of production processes based on abrasive flow machining

In Russia, the ability to process the abrasive flow of parts from aluminum alloys is confirmed. The empirical dependences of the scratch depth from the type of abrasive grain on the sample of aluminum alloy AMG-6 are determined. Recommendations are given on the choice of the composition of the medium and the mode of processing parts from aluminum alloys [24], including rectangular openings with a length of 10 mm and a cross section of $2 \times 0.625$ mm [25]. The possibility of using AFM is investigated to reduce surface stresses in the channels of parts after the electric erosive processing [26].

The technique of six stages is proposed, which allows optimizing the costs production of technological preparation [27]. An approach is proposed, in which for each stage of the life cycle of the AFM environment for AFM, a set of factors and response functions is determined. At the next stage of the life cycle, the response function of the previous stage becomes factors (source data). The life cycle includes five stages divided into thirteen steps. Based on the analysis of world experience for each stage, a set of factors is proposed to allow the characteristic of the processed part, the composition of the medium, processing modes, as well as contact interactions [28].

3.1. Machining with an abrasive flow of parts with a variable shape

Experimental machining of the abrasive flow of parts with a cylindrical and conical channel showed the unevenness of the removal of material and changes in roughness. Non-uniformity is caused by the restructuring of the flow profile. To ensure uniform processing of such channels, a device that align the channel cross-section by its length is proposed. In this case, there is a transition from the flow of medium through local resistance (cone) to the flow in the ring channel (figure 3) [29]. To confirm the experimental results and processing modelling, a device is made (figure 4) [30].

![Figure 3](image)

**Figure 3.** AFM scheme using an alignment device: 1 - upper adapter; 2 - detail; 3 - lower adapter; 4 - base; 5 - gaskets; 6 - an alignment device [29].
Figure 4. Device: a) 1 - cover; 2 - body; 3 - cylindrical part of the channel; 4 - conical part of the channel; 5 - grooves for removable samples; b) levelling devices that implement different cross-sectional area of the ring gap [30].

Figure 5. The original state of the sample surface before AFM: a) the general type of sample, b) an increase of 63 times [30].

Figure 5 shows a general view of the sample and the initial state of its surface before AFM. Figure 6 shows a general view of the sample and the roughness of its surface after 30 AFM cycles. The machining of the abrasive flow with the use of the levelling device made it possible to provide uniform roughness in the channels with a variable cross section.

Figure 6. Status of the sample surface after 30 cycles of AFM: a) General view of the sample, b) an increase of 63 times [30].

3.2. Machining by the abrasive flow of parts made of molybdenum alloys
For finishing processing of billets from molybdenum powder alloys, the treatment powder with an abrasive flow of high-viscous medium is processed. To do this, the model for removing the material with a single abrasive grain is specified. In this model, the abrasive grain is a multi-season tool acting on the surface being processed, both by the actual contact area, and along the contour contact area.
Based on these features of the contact, the abrasive stream was treated in two stages of the billet from the powder molybdenum alloy. The initial state of the surface has a roughness of $Ra = 1.6 \mu m$ [32].

![Figure 7. The surface of the workpiece of molybdenum powder alloy after abrasive flow machining [32].](image)

For processing at the first stage, a normal electrocorundum of graininess F40 and an extrusion pressure of 12 MPa is applied. It was possible to obtain the surface roughness $Ra = 1.45 \ldots 1.5 \mu m$. For AFM at the second stage, high-viscous medium is used, in which the grains of silicon carbide are used by the graininess of the F80. The magnitude of the extrusion pressure is 12 MPa. The roughness of the surface of the blank $Ra = 1.3 \ldots 1.4 \mu m$ (figure 7) was obtained. Its texture is characterized by the absence of protrusions and wrappings, whose sizes would be much more average roughness. The possibility of the applicability of the Machining with an abrasive flow by high-viscous medium for finishing processing of billets from powder molybdenum [32] is experimentally confirmed.

4. Conclusions

The following conclusions can be drawn from the review presented in this article. In Russia, bidirectional abrasive flow machining received the greatest distribution. A number of devices, fixtures of the compositions of media and processing methods have been developed.

For successful AFM modelling in Russia, a number of studies on the rheology of the medium were conducted. Coefficients of effective viscosity, numerical values of the Young module and the Poisson rate for high viscosity medium are experimentally defined. Based on these data, the rate of shift, the value of tangent stresses and normal voltages of the high viscosity medium in the cylindrical channel is calculated.

Visual studies of the stream of medium in channels of various geometric shapes experimentally confirmed theoretical assumptions: the emergence of elastic (normal stresses) in the medium stream; the movement of abrasive particles in the stream of medium over the current lines to form an elastic (power) chain.

To simulate AFM channels of large length, a model of the flow of a viscoelastic medium filled with abrasive particles is proposed. It is proposed to use polydisperse media filled with abrasive grains of several grain. They are characterized by a more rigid structure.

For all types of contact, formulas are proposed to determine the actual contact area of micron of abrasive grain and the treated surface. On their basis, the equations are proposed to determine the volume of the material being removed and the roughness of the treated surface.

A new method of machining with an abrasive flow, which ensures uniformity of the removal of material and roughness in the conical channels is developed. To do this, an aligning device is applied, which provides the transition from the flow of medium through the local resistance (cone) to the flow in the annular slit.
The processing of the abrasive stream is successfully applied to the finishing of the part of the powder molybdenum.

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