The research of the agglomeration process during the formation of an abrasive-polymer compound for waterjet cutting in a fluidized bed installation

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Received: 14 January 2021 / Accepted: 20 April 2021 / Published online: 28 April 2021 © The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2021

Abstract

The article deals with the issues that allow creating conditions that exclude the formation of abrasive agglomerations in the process of applying a polymer coating in installations with a fluidized bed. The authors pay attention to the stages of agglomeration of the abrasive in the fluidized bed, as well as possible situations that arise when one particle collides with another. The problem of agglomeration development in the installation chamber is relevant, as it directly affects the quality of the coating, its uniformity. In addition, the critical size of the agglomerations will stop the coating process and lead to large material losses. The research carried out in the article on the process of obtaining a new effective abrasive material for waterjet cutting makes it possible to increase the cutting capabilities of a waterjet.

Keywords Waterjet cutting · Abrasive particle · Polymer shell · Fluidized bed · Agglomeration

1 Introduction

Waterjet cutting is one of the most advanced and popular technologies in the world [1–9]. It has found successful applications not only for cutting any materials in the industry but also for deep-sea repair, defragmentation, and cleaning of sea laying pipeline systems, including in the Arctic.

With the help of waterjet cutting, it is possible to cut almost any material:

- Ferrous and non-ferrous metals and their alloys (including copper, nickel, brass, aluminum, magnesium, titanium, and their alloys) [10]
- Hard-to-work alloy steels and alloys (including heat-resistant and stainless) [11]
- Composite, porous, cellular, foam, rubber [12]
- Natural and artificial stones, ceramic materials, glass (tiles, granite, marble, etc.) [13]
- Concrete and reinforced concrete [14]

As a working material in this technology, the garnet is typically used, as it is a strong abrasive (over 7.5 on the Mohs scale) with rounded edges that allows authors to slow down the wear of the nozzle focusing tube of the waterjet installation. The garnet is mined in Australia, South Africa, the USA, India, and China; companies around the world, including Russian ones, use it despite the high price. The use of more affordable superhard abrasives (elbor, boron carbide, silicon carbide, electro corundum) was impossible due to the critical wear of the focusing tube of the nozzle (several minutes).

Due to the shorter service life of the focusing tubes, these types of abrasives are only used in special cases where it is economically feasible [15].

The problem of using olivine and glass as a cheaper analogue of garnet in the waterjet cutting of the popular titanium alloy grade 5 (Ti6Al4V) is discussed in the work of Perec [10]. It is established that the garnet abrasive material provides the greatest depth of cut. The use of an olivine abrasive material resulted in a slight 10% reduction in the maximum cutting depth. Broken glass showed even worse possibilities (on average, the cutting depth decreased by 20%).

The authors propose to create a new composite material obtained by coating the abrasive grain with a protective
polymer shell to prevent the negative impact of the contact of the abrasive with the surface of the nozzle tube, and this will significantly increase the efficiency and expand the possibilities of waterjet cutting.

2 Main part

During the abrasive processing in the fluidized bed, the particles repeatedly collide with each other, which are accompanied in some cases in the presence of a liquid by their union or agglomeration. Of course, two, three, or more particles can be combined in the collision process. The authors can ignore this and consider only the paired agglomeration [16].

Consider the stages of agglomeration of abrasive in a fluidized bed:

1. Primary agglomeration. At this stage, the strength of the stuck agglomerates together is low, so when it is exposed to other particles colliding during processing, such a bond is quickly destroyed. This stage does not affect the quality of the polymer coating on the abrasive; the layer will be uniform.

2. Sustainable agglomeration. This stage is accompanied by the formation of agglomerates with sufficiently strong bonds that are not destroyed during movement in the fluidized bed. Maintaining the bond between the particles leads to even more abrasive sticking and an increase in the size of the agglomerates. In addition, since there may be several stuck particles in the layer, it is possible to combine them into one agglomerate. Further development of this process leads to the transition to the third stage of agglomeration.

3. Deposition. The size of agglomerates reaches such a value when it is impossible to hold them in a suspended state in a fluidized bed. This development will lead to the deposition of agglomerates on the structural elements of the coating plant. In the zone where the agglomerate settles, the air flow will flow around the obstacle, which will create conditions for additional deposition of particles on the settled agglomerate. In this zone, the drying process will be difficult; heat exchange with the environment will slow down, which will lead to an increase in temperature and melting of the polymer coating and increase the strength of the agglomerate. Further operation of the fluidized bed coating unit is not possible and requires a cleaning of the treatment area to continue.

4. Adhesion. Agglomerates that have grown to a critical size can no longer be supported in a suspended state by a fluidizing agent having a certain speed; they are deposited on the gas distribution grid. From this point on, the adhesion begins. Above the settled agglomerate, a stagnant zone is formed, where other agglomerates and particles rush. Both in the stationary and in the boing layer, due to the deterioration of heat exchange, the mass of particles and agglomerates is strongly overheated; its melting begins. At this stage, the process stops. Such an emergency state of the system can be eliminated only by disassembling the device (machine), and its cleaning is often carried out manually. This leads to extremely large material losses.

The occurrence of agglomerations can be observed both at the first and at the second stage in any area of the installation chamber. When creating a fluidized bed, when the speed of the air flow raises part of the abrasive particles, the other is already at this point prone to the formation of agglomerates of the chamber. At this time, the air flow flows around a part of the particles lying on the grid of the chamber. Further increase in air flow rate and velocity destroys these stagnant zones. However, if the particles are wet and conditions are created for them to stick together, an increase in the flow rate will not have any effect on their destruction and involvement in the fluidized bed. The process can only be accompanied by further consolidation of agglomerates (Fig. 1).

The paper considers the conditions of adhesion in a developed fluidized bed. At the same time, it is shown that particles, whose protective shell has not hardened yet and is liquid, are prone to sticking together. Adhesion occurs during the impact of two particles (triple collisions are neglected). Before the impact, the particles moved relative to each other and had certain absolute velocities \( \vec{v}_1 \) and \( \vec{v}_2 \) and the relative velocity \( \vec{v}_{12} = -\vec{v}_{21} = \vec{v}_1 - \vec{v}_2 \) of the first particle with the mass \( m_1 \) relative to the second particle with the mass \( m_2 \). It is assumed that before and after the collision, the total mass of the particles, as well as the mass of each of them, with the

Fig. 1 Agglomeration of abrasive particles in the formation of an abrasive-polymer shell compound for waterjet cutting. 1, abrasive no. 1; 2, abrasive no. 2; 3, abrasive no. 3

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exception of the negligible mass of possible lost droplets of the liquid shell, is preserved:

\[ m_1 + m_2 = \text{const} \quad (1) \]

In addition, it is believed that the impact of particles against each other is absolutely inelastic, since the opposite case involves the separation of particles from each other after the impact. This assumption means that after the impact, the total momentum that the particles had before the impact is preserved. In this case, the condition of equality of particle velocities after impact is met. The condition of conservation of their total energy, which is characteristic of an absolutely inelastic impact, is not fulfilled. It is replaced by the condition of equality of velocities-particles, stuck together, formed a single body. Let \( \vec{v}_1', \vec{v}_2', \) and \( \vec{v}_{12} = -\vec{v}_{21}' \) be the corresponding velocities of the particles \( m_1 \) and \( m_2 \) (authors will denote them by denoting their masses) after the end of the impact (it is assumed that it lasts a certain time \( \tau \) from the moment of contact of the particles to the moment when the relative motion ends). Then the comparison of the characteristics of the particles before the impact and after it ends leads to the equalities:

\[ m_1 \vec{v}_1 + m_2 \vec{v}_2 = (m_1 + m_2) \vec{v}', \vec{v}_1' = \vec{v}_2' = \vec{v} \quad (2) \]

Two particles will stick together if they move at different speeds and if the energy of their relative motion after impact is equal to zero.

The inequality of initial velocities means, if their values are equal, the absence of parallelism or crossing of the directions of their vectors, and if they are unequal, the directivity along one straight line or parallel lines is located in a tube with a diameter equal to the sum of the diameters of colliding particles (Fig. 2). In this case, the initial kinetic energy \( W_{k(12)} \) of the relative motion of the particles \( m_1 \) and \( m_2 \) must be lost completely or partially to viscous friction in the liquid shells during the time \( \tau \). This energy can be calculated. Regardless of the developing impact of particles—direct (frontal), tangential, or intermediate between these types—the magnitude \( W_f \) of the work of viscous friction forces is largely determined by the viscosity coefficient of the liquid shells.

Particles that are brought closer together by impact fall under the action of long-range adhesive forces [16]. These particles will stick together if their total energy \( W_a \) is greater than their kinetic energy when they collide, minus the work of the viscosity forces of their liquid layers:

\[ W_{k(12)} - W_f \leq W_a \quad (3) \]

From Formula (3), it can be seen that the process of adhesion of pairs of particles, their agglomerations, will be the more intense for the pair of particles for which the magnitude of the kinetic energy of relative motion will be less, and the work of viscous forces is greater. The greater the work \( W_f \), the greater the viscosity of the shells of abrasive particles, provided that their liquid state is preserved. Agglomeration of sticking pairs of particles will take place faster where there is a greater probability of their collision, that is, where their concentration is greater. Maintaining the liquid state, the viscosity of the polymer liquid significantly depends on the local temperature of the process, length, and shape of the macromolecules. Further, the impact of each of the reasons is considered separately.

The stability and reliability of the fluidized bed are influenced by the nature of heat and mass transfer. Lykov [17] showed that the transfer of heat and substance cannot be considered separately independently of each other, but only in their relationship. The worst heat transfer occurs in those
environments where aggregation is most pronounced. The temperature in the clot can reach the melting point of the material. The resulting local overheating zones are the main cause of the development of agglomeration, due to the appearance of the liquid phase in these zones. A decrease in the porosity of the system leads to fluctuations in the thermal equilibrium. An increase in temperature changes the ratio of solid and liquid phases in favor of the latter, and this, in turn, stimulates the aggregation of particles. For the solid part, the addendum $W_f$ in inequality (3) is missing. When the particles overheat, their shell can go into a liquid state so that the addendum $W_f$ will be non-zero and the inequality will be satisfied for a larger number of particles $W_f$ than in the absence. The speed of aggregation will increase.

In this paper, a new, but already quite common water-soluble polymer shell, polyoxymethylene, is considered a coating of abrasive particles. It is obtained by polymerization of oxyethylene. Polyoxymethylene is known abroad as Polyox (polyox) and is a high-molecular polymer shell of ethylene oxide with a molecular weight of several hundred thousand to five million. Polyox is produced under various brands that differ in molecular weight. Polyoxymethylene is thermostatic; its melting point is 66–67°C. At a temperature of 150°C, the polymer shell forms a viscous melt without noticeable degradation.

To answer the question of whether the coated abrasive particles will stick together or not, based on the solution of the Langmuir equation, the authors conclude that the shell will harden or not by the time one particle collides with another. To do this, three possible situations are considered:

1) A drop of polyethylene oxide dissolved in water, formed at a height of $h$, fell to the bottom (after the formation of the fluidized bed, the thickness $h_0$ of the abrasive embankment equals to zero or tends to it $h_0 \to 0$). At the same time, in the oncoming air flow, the water from the solution evaporates, and the polyethylene oxide hardens. The question is whether these processes will be completed by the time of the fall or not. At this point, the remaining drop material may collide with the bottom or a new $h$ particle of abrasive.

2) At the height of $h$, the drop immediately hits the abrasive particle and falls with it, spreading over its surface. The question is how soon the water will evaporate from the coating and the polyethylene oxide will solidify, whether the end time of the process is commensurate with the average time between collisions of particles in the layer.

3) In the previous case, the protected particle reaches the bottom and collides with it. The question is whether the protective shell is in a liquid or solid state at this moment.

The review is carried out under the condition that the initial $T_0$ and final $T_1$ temperatures in the working chamber are known. The origin $y = 0$ of the vertical coordinate $y$ is placed at the bottom of the chamber. The temperature distribution $T(y)$ over height is assumed to be linear for ease of calculation.

$$T(y) = T_1 + \frac{T_0 - T_1}{h} (y - 0) \tag{4}$$

The air speed $v_a$ in the upstream flow is known and is considered constant over the entire segment $y \in [0, h]$. The thermodynamic parameters of air and water vapor from the drop, as well as the size of the drop, and the concentration of water in it are also considered known. The speed of the droplet $v_d$ and abrasive particle $v_p$ are determined by the conditions of vertical motion in the upward flow and the field of gravity. The initial characteristics of the movement are agreed when specifying these conditions. When moving up, $v_d > 0$ and $v_p > 0$; when moving down, $v_d < 0$ and $v_p < 0$.

First, the authors consider the vertical motion of a ball of radius $R$ in the air flow in a gravitational field with the acceleration of free fall $g$. The mass of the ball is equal to $m = \frac{4}{3} \pi R^3 \rho$, the speed of movement $v = \frac{dy}{dt}$. The speed of the ball is considered small. So, as the law of interaction between air and a ball, the authors can use Stokes law with force $f = -c(v - v_a)$, where $c = 6 \pi \mu R$; $\mu$ is the dynamic viscosity of the liquid. Depending on the situation of resistance, this force can be both a resistance force and a force that pushes the ball. In different situations, the ball simulates an evaporating droplet or a protected or unprotected abrasive particle. In all cases, the mass of the ball is considered constant. In cases where the movement is accompanied by evaporation, the particle mass is taken as a value equal to the half-sum of the masses at the beginning and end of the way.

The differential equation of ball motion has the following form.

$$v = \frac{dv}{dt}, \quad \frac{dv}{dt} = mg - c(v - v_a) \tag{5}$$

General solution of this equation:

$$v = C_1 e^{-c/m}t + v_a \left(\frac{m}{c}\right)g$$

$$y = C_1 \left(\frac{m}{c}\right) e^{-c/m}t +$$

$$+ \left[ v_a \left(\frac{m}{c}\right)g \right] t + C_2 \tag{7}$$

The integration constants $C_1$ and $C_2$ are determined based on the initial and final conditions. In each task, they are different.

For a falling liquid drop, the authors assume that its final mass is zero—in this case, it falls more slowly. This means that the humidity in the air and the possibility of abrasive particles to stick together are more evident. This is the worst option for the workflow. In this case, $m = \frac{m_0}{2}, y(0) = h, v(0) = 0 \tag{8}$
The solution gets the following form:

\[
C_1 = \left( \frac{m}{c} \right) g v_a, \quad v(t) = \left[ v_a - \left( \frac{m}{c} \right) g \right] \left( 1 - e^{-\left( \frac{c}{m} \right) t} \right)
\]  

(9)

\[
C_2 = C_1 \left( \frac{m}{c} \right) + h = \left( \frac{m}{c} \right) g v_a \cdot \left[ \left( \frac{m}{c} \right) g v_a \right] + h.
\]

(10)

\[
y(t) = h + \left[ \left( \frac{m}{c} \right) g v_a \right] \cdot \left[ 1 - \left( \frac{c}{m} \right) t e^{-\left( \frac{c}{m} \right) t} \right]
\]

(11)

Falling from a height \( h \), the liquid particle evaporates. In the aerosol method of coating abrasive particles, the evaporation process can be described by the Langmuir equation for concentration in \( \text{mmHg} \), which increases with the temperature rise above the bottom of the chamber, the solution particle instantaneously turns into a polymer particle. Its size corresponds to its non-solid state will settle to the bottom of the fluidized bed is determined from the graph shown in Fig. 3 also indicates that a decrease in temperature to room value does not significantly affect the rate of evaporation of water from the polymer solution. This conclusion allows authors to reduce the temperature of the coating process in order to get on the abrasive particles of the polymer shell crystallized as quickly as possible. In this case, the agglomeration of particles with a freshly made coating will be less due to the fact that at low temperatures, the coating is more elastic and the energy loss of colliding particles to dissipation is reduced. So the potential compression energy of the coating is able to overcome the adhesion forces (see the analysis of Formulas (2) and (3)).

There is a question about whether the polymer particles in the non-solid state will settle to the bottom of the fluidized bed, sticking together to form an agglomerate. The answer to this question is based on the Formulas (9) and (11). Considering the high rate of evaporation of the solvent–water, the authors can say that after injecting the solution at a height \( h \) above the bottom of the chamber, the solution particle instantly forms a polymer particle. Its size corresponds to its concentration in the solution. Instantaneous formation means that the initial velocity of the polymer particle is zero.

From Formula (9), it follows that the polymer particle will start moving down if

\[
\nu_a < \left( \frac{m_{pol}}{c_{pol}} \right) g 
\]

(15)

In this formula, the value of the velocity of the upward air flow \( \nu_a \) forming the fluidized bed is determined from the working process. The authors assume (with brute force) that a drop consists only of water. For calculations, the following values included in Formula (13) are accepted.

\[
\rho = 1 \text{ g/cm}^3, \quad d = 50 \cdot 10^{-4} \text{ cm}, \quad T = 343^\circ \text{K} \left( = 65^\circ \text{C} \right), \quad p_{x,v} = 234 \text{ mmHg}, \quad M_{mol} = 18 \text{ u}.
\]

As a result, it is obtained that a drop of water with such characteristics at the selected temperature will completely evaporate within \( t = 0, 26 \cdot 10^{-3} \text{ s} \).

That is, the water from the drop evaporates very quickly.

Figure 3 shows the dependence of saturated water vapor pressure on temperature. Obviously, this pressure increases with increasing temperature. Moreover (authors can check), this pressure increases faster than the growth of the root \( \sqrt{T} \) included in Formula (12). That is, the function \( \tilde{p}(T) = p_{x,v} / \sqrt{T} \) is increasing. So with the increasing temperature, evaporation occurs faster—an obvious fact, quantitatively described by the above dependencies. This circumstance is convenient for the manufacture of a coating of abrasive particles because it indicates the way of release of the polymer shell from the aqueous solution before it meets the abrasive particles. The graph shown in Fig. 3 also indicates that a decrease in temperature to room value does not significantly affect the rate of evaporation of water from the polymer solution. This conclusion allows authors to reduce the temperature of the coating process in order to get on the abrasive particles of the polymer shell crystallized as quickly as possible. In this case, the agglomeration of particles with a freshly made coating will be less due to the fact that at low temperatures, the coating is more elastic and the energy loss of colliding particles to dissipation is reduced. So the potential compression energy of the coating is able to overcome the adhesion forces (see the analysis of Formulas (2) and (3)).

The coating polymer shell for further spraying comes in the form of an aqueous solution. To analyze the situation, the authors will estimate the evaporation time of a single drop of sprayed solution under conditions close to those used in the
condition of its stability. A rough condition for this is equality.

\[ v_B = \left( \frac{M_{abr}}{c_{abr}} \right) g \]  \hspace{1cm} (16)

This value has an order \( v_a = 1 \text{ m/s} \).

Assuming that the polymer particle has the shape of a ball of diameter \( d_{pol} \) with the density of the material \( \rho_{pol} \), taking into account that the coefficient of resistance to its movement in air \( c_{pol} = 3\pi \mu d \), for the right part of the inequality (15), the authors can obtain

\[ \left( \frac{m_{pol}}{c_{pol}} \right) g = \rho_{pol} g \frac{d_{pol}^2}{18 \mu} \]  \hspace{1cm} (17)

From this, it can be seen that the larger the particle, the greater the probability that the inequality (15) will be fulfilled, and the particle will settle to the bottom of the chamber. Therefore, an estimated calculation was performed for a large particle under the assumption that the polymer particles remaining after evaporation, agglomerating with each other, reached the size of the solution particles, for the following data.

\[ \rho_{pol} = 1.2 \cdot 10^3 \text{ kg/m}^3, \quad d_{pol} = 50 \cdot 10^{-6} \text{ m}, \quad \mu = 200 \cdot 10^{-6} \text{ P}\times \text{m}/\text{N}\times \text{s}. \]  \hspace{1cm} (18)

It is obtained that in the considered case,

\[ \left( \frac{m_{pol}}{c_{pol}} \right) g = \rho_{pol} g \frac{d_{pol}^2}{18 \mu} \cong 0,5 \text{ m/s} \]  \hspace{1cm} (19)

This value, although less than \( v_a = 1 \text{ m/s} \), indicates that there is no settling of polymer particles to the bottom but is commensurate with it. Considering the approximate nature of the assessment, authors can say that when agglomerates of polymer particles appear, the probability of their deposition is not zero.

The obstacle to such agglomeration are the temperature rise—it increases the viscosity of air and, consequently, increases the removal of not deposited particles of polymer shell on the abrasive from the working area (the theoretical dependence of the Sutherland viscosity on temperature is presented in book [20]) and the reduction of the concentration of the polymer solution; during evaporation of the solvent, the concentration of polymeric particles in the air will be less than if the concentration of the solution is great.

Ensuring non-compliance with equality (15) contributes to the fact that the aerosol of the polymer solution forms a cloud in the upper part of the fluidized bed that does not settle to the bottom of the chamber. It should be noted that the high temperature in this cloud, close to the melting point of the polymer shell, plays a negative role, since the polymer layer deposited on the abrasive particles in a near-liquid state during the collision of particles contributes to their adhesion and the appearance of agglomerates.

The authors of the article conducted a comparative analysis of the quality of waterjet cutting using garnet sand mesh 80 (GMA) and SIC abrasive in a polymer shell (Russia). A steel sheet with a 45 DIN thickness of 50 mm was used as a blank. Cutting modes pressure \( p = 400 \text{ MPa} \), tube diameter \( d = 1.02 \text{ mm} \), abrasive consumption 400 g/min. The blank was cut out (Fig. 4), and then the surface quality was measured using a profilometer-profilograph.

Based on the results of the measurements, the following conclusions are made:
1. The surface roughness after cutting with garnet sand (GMA) and SIC abrasive in the polymer shell corresponds to the roughness $Ra = 1.8 – 3.2 \ \mu m$.

2. The cutting taper of the SIC abrasive cut in the polymer shell at a nozzle feed rate of 20 mm/min is 5% less than when using garnet sand (GMA) at the same feed.

3. The jet lag is less by 2–3% when cutting with SIC abrasive in a polymer shell than with garnet sand (GMA). This is due to the fact that the abrasive ability and strength of the abrasive grain of silicon carbide are higher than that of garnet. This allows authors to increase the cutting speed by 10–20% and provide a quality comparable to the use of garnet sand (GMA).

In addition to the difference in the maximum flow, the nozzle wear was evaluated. After working on an uncoated SIC abrasive and on the same SIC abrasive with a polymer shell, the focusing tubes were cut along the axis, and the degree of wear was compared. Photos of sections of the focusing tube are presented in Fig. 5.

Visually, it can be seen that the wear of the focusing tube was significantly reduced when using SIC abrasive with a polymer coating. When using an abrasive without SIC coating, deep waves are observed after 15 min (Fig. 5a), leading to a loss of nozzle performance. The polymer shell on the surface of the SIC abrasive retained the ability of the focusing tube to form a waterjet after 30 min of operation.

3 Conclusions

On the basis of the arguments presented in this paragraph, the authors can state the following. Agglomeration of sticking pairs of particles will take place faster where there is a greater probability of their collision, that is, where their concentration is greater. Maintaining the liquid state, the viscosity of the polymer liquid is significantly dependent on the local temperature of the process. For the successful operation of coating abrasive grains, the temperature in the spray zone of the polymer solution must be close to the melting point of the polymer.

![Fig. 4](image_url) Part C45 DIN steel after waterjet cutting using SIC abrasive in a polymer shell

![Fig. 5](image_url) Photos of the wear of the focusing tube channel. a The channel of the focusing tube when working on the initial SIC abrasive for 15 min; b the channel of the focusing tube when working on the SIC abrasive with a polymer coating for 30 min
shell, but below it. A high temperature value promotes rapid evaporation of the solvent-water, which reduces the probability of small drops of solution merging into large ones falling to the bottom of the chamber. At temperatures lower than the melting point of the polymer shell, they harden quickly without solvent, and in the solid state, their agglomeration is unlikely. It is shown that the use of an abrasive with a polymer coating allows the authors to save the focusing tube and improve the quality of the treated surface.

Availability of data and material
Not applicable.

Code availability
Not applicable.

Funding
This research was supported by the Russian Science Foundation, grant no. 20-79-00347.

Declarations

Conflict of interest
The authors declare no competing interests.

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