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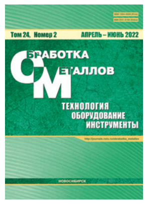

Theoretical simulation of the process interelectrode space flushing during copy-piercing EDM of products made of polymer composite materials

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ABSTRACT

Introduction. Polymer composite materials (*PCM*) are used to improve the mechanical properties and increase the working period of products. For the processing of products made of *PCM*, the use of electrophysical processing methods is standard. One of these methods is copy-piercing electrical discharge machining (*EDM*). The use of such methods for processing *PCM* is due to its high physical and mechanical characteristics and the complexity of processing by blade methods. Considering the fact that the *PCM* element is a binder – epoxy resin, which is destroyed at the edges of the resulting holes and grooves during *EDM*, *PCM* can be considered difficult to process. During the *EDM* of holes in *PCM* products, the temperature rises, and inefficient cooling often occurs in the processing zone. The paper is devoted to theoretical simulation in the *Ansys* package, which makes it possible to evaluate the impact of flushing method on the efficiency of the *EDM* of *PCM* products based on numerical simulation in finite element analysis software systems. The aim of the work is to increase the productivity of the processes of *EDM* for *PCM* products. **Methods.** Experimental studies were carried out according to the method of a classical experiment on a copy-piercing electrical discharge *Smart CNC* machine. The workpiece was processed at a constant voltage U = 50 V, pulse on-time T_{on} = 100 µs and current: I = 10 A. For theoretical simulation of the flow, the *ANSYS CFX 20.1* software was used. Flow distribution simulation was carried out at three processing depths (2, 10, 15 mm), as well as at three nozzle inclination angles (15, 45, 75°). **Results And Discussion.** The analysis of the data obtained showed that in the case of the *EDM* of *PCM*, the angle of the location of the flushing nozzles should be taken into account in order to increase the productivity of processing deep, blind holes. It is established that the highest performance value is achieved when the nozzles are located at an angle of 15˚. The laminar motion prevails. With this arrangement of the nozzles, the value of the liquid pressure and the removal of the sludge are stable both with the *EDM* of *PCM* to a depth of 2 mm, and when processing to a depth of 15 mm. It is noted that for processing holes with a depth of 10 mm or more, it is worth considering the angle of inclination of the flushing nozzle for effective processing, it is necessary to remove eroded particles from the gap. In the process of conducting an experimental study, when processing holes with a depth of 15 mm, sticking of sludge to the electrode-tool was observed, as well as the closure of the *EDM* process, the occurrence of secondary discharges in the processing zone, which caused the processing to stop.

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Introduction

The branches of modern mechanical engineering, aviation, oil and gas are associated with the introduction of new materials and innovative technologies. It is relevant to develop and improve the efficiency of processing technologies for new polymer composite materials (*PCM*), as well as form of the required physical and mechanical properties of products made from these materials [1].

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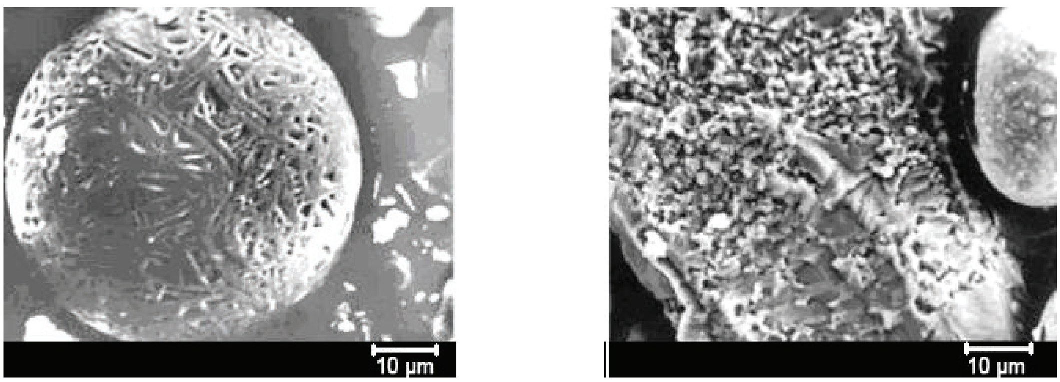
Today, there is a diverse range of *PCM;* new promising materials based on carbon fiber, developed at FSUE "VIAM", are of particular interest. One of these materials is carbon fiber prepreg grade *Vku-39/Vtku-2.200*. This material is made on the basis of equally strong carbon fabric grade *VTkU-2.200* and binder grade *VSE-1212*. To process products made of *PCM*, including carbon fiber reinforced plastics of the *VKU-39*, it is advisable to use electrophysical processing methods. Copy-piercing electrical discharge machining (*EDM*) is one of these methods. The use of such processing methods for *PCM* is due to its high physical and mechanical characteristics and the complexity of processing by blade methods. Considering the fact that the *PCM* element is a binder – epoxy resin, which is destroyed at the edges of the resulting holes and grooves during *EDM*, *PCM* can be considered difficult to process. During the *EDM* of holes in *PCM* products, the temperature rises, and inefficient cooling often occurs in the processing zone [2–3].

In papers [4-6] the methods and features of the *EDM* of *PCM* are presented. On the basis of these works, it is shown that a product made of *PCM* is subjected to the action of electrical impulses during *EDM*. The plasma channel appears and has an internal temperature of about 9,000-9,500 °C. This leads to a change in the state of the *PCM* material. A phase transition occurs from a solid material to a vaporous substance. This subsequently leads to the fact that *PCM* vapors and molten pieces of electrode-tool (*ET*) sludge solidify upon cooling and form products of electroerosive sludge, which negatively affects the quality and performance of the *EDM* [7, 8].

Accumulation of erosive sludge and other erosion products in the zone of *EDM* of *PCM* products is caused by poor flushing of the space between the *ET* and the workpiece being processed when deep holes are obtained, as well as slotted and key grooves. This phenomenon leads to the appearance of secondary dendritic structures on the surface of the *ET* and the workpiece, as well as to a decrease in the *EDM* quality and productivity when processing products made of PCM [7].

It has been established that the movement of sludge during the *EDM* of *PCM* products is formed by the process of formation and movement of gas bubbles in the processing zone [8–11]. Due to the fact that the dielectric (usually mineral or transformer oil) is viscous, electroerosion sludge can move in the shell of the gas bubble. As a result of the studies carried out in [8–11], it becomes possible to show visually the process of erosive sludge movement in the interelectrode space. It is proposed to vary the parameters of the height of the rise of the *ET* from the zone of the *EDM*, as well as the speed of the rise of this *ET*. However, in these works there are no practical recommendations for increasing the productivity and efficiency of the *EDM* of *PCM* products.

The structure of erosive sludge is shown in [12, 13]. This sludge is obtained as a result of the destruction of *ET* and the workpiece material. This forms spherical and hemispherical particles shown in Figure 1, *a*. The direct formation of the shape of particles in the form of a sphere occurs in the process of cooling the evaporated material of the workpiece. Most of the obtained spherical and hemispherical particles of erosive sludge have a dendritic structure. This indicates the low cooling rates of the *EDM* process. The formation of erosive sludge from the destroyed *ET* occurs by thermal crumbling (Figure 1, *b*).

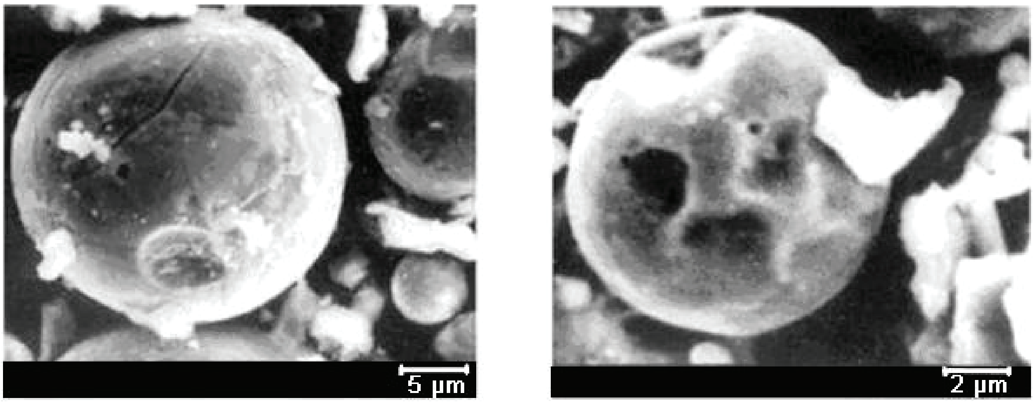


a *b*

Fig. 1. EDM sludge:

a – from the workpiece surface; *b* – from the surface of the electrode-tool

EDM sludge particles are subject to destruction. Cracks, dents, as well as zones of crumbling and destruction appear on the surface of spherical particles with an increase in the value of the pulse energy (Figure 2).



a *b*

Fig. 2. The surface of spherical sludge particles after destruction:
a – at a scale of 5 μm; *b* – at a scale of 2 μm

Local heating of the processed material causes thermal decomposition of the boride phase and the dielectric medium [14, 15]. This dielectric processing medium is in a state of motion and constant circulation. This leads to cooling of the *ET* and the workpiece material. The flow of vapors becomes turbulent and can break up into small fractions. Each part can condense into a liquid, and as a result, into a solid state.

The cooling rate of liquid metal drops is reduced by the vapors of the working fluid that promotes spheroidization and dendritic segregation of particles. The content of the working fluid and metal vapors decreases at low input energy. This leads to a decrease in the number of particles with a smaller average size. The sludge solidifies faster if the pulse energies are not high. The flow of material vapors and the working fluid increases along with the values of the input pulsed energy [14, 15]. The movement of sludge particles is turbulent. There is a collision between it. Cracks and dents form on the surface of the particles of this sludge and an inclusion structure also appears. The formation of *EDM* sludge significantly affects the stability of the *EDM* process and, as a result, the productivity of processing.

Increasing the productivity of the *EDM* process can be achieved not only by increasing the pulse energy, but also by intensifying the removal of erosion products from the interelectrode gap. Productivity increases with effective flushing and intensive removal of eroded particles of *PCM* and *ET* from the gap. Flushing brings clean gear oil into the gap and cools the *ET* and *PCM*. The deeper the treatment, the more difficult it is to ensure proper flushing of the zone being processed. This increases processing time and reduces performance. Eroded particles are welded onto a *PCM* product under certain processing conditions. This leads to uneven processing and reduced performance or even to its stop.

Flushing is widely used in *EDM* of deep holes, including *EDM* of *PCM* products. Insufficient flushing reduces material removal efficiency. The material that remains in the hole is remelted in the next pulse and welded onto the electrode surface.

The intensification of flushing during *EDM* in deep and narrow cavities contributes to an increase in the material removal rate. In [16, 17], it was found that flushing maintains the rate of material evacuation after a discharge. In [17], the effect of the *ET* jump was studied, which is used to evacuate eroded material during immersion under pressure. The electrode movement speed affected the distribution of eroded particles, and the movement amplitude affected the amount of pure dielectric.

The work [18] shows the pressure drop of a dielectric liquid at the hole depth, the influence of the hole depth on the pressure drop. This was a loss of 15% of the observed 25 mm. A higher concentration of eroded material was also established in the corner of the machined hole (Figure 3).

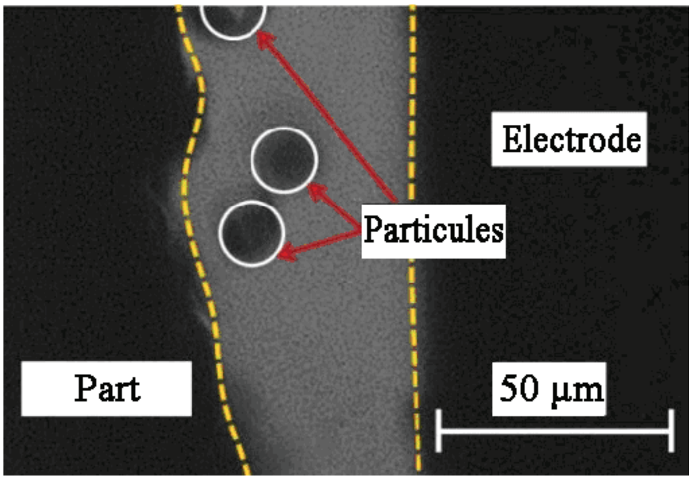


Fig. 3. Partial tracing in the gap between the electrode and the workpiece. The average particle velocity is approximately 0.75 m/s

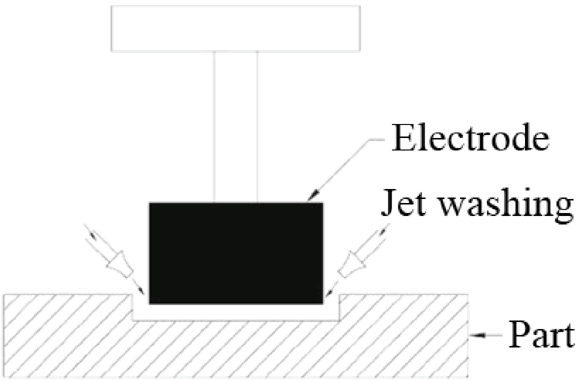


Fig. 4. Scheme of jet or side flushing

Jet or side flushing is carried out with tubes or flushing nozzles. These nozzles direct the dielectric fluid into the gap. This is shown in Figure 4.

Efficiency of flushing in the case of *EDM* of deep holes in *PCM* with a complex geometry of electrode flushing channels has not been practically studied in full. Existing models in the processing of *PCM* by electrical discharge can be obtained using theoretical simulation in finite element analysis software systems, including *Ansys*.

An urgent task is to obtain a theoretical model. This model will make it possible to evaluate the influence of the flushing method on the efficiency of the *EDM* of *PCM* products based on numerical simulation in finite element analysis software systems.

The aim of the work is to increase the productivity of the process of *EDM* of products made from *PCM*.

Tasks.

1. Carry out a theoretical analysis of the effect of flushing the nozzles of the working fluid on the process of the *EDM* of products made from *PCM.*

2. To carry out an experimental study of the performance of the process of *EDM* of products made from *PCM* and verification of the theoretical model of the performance of *EDM* of products made of *PCM*.

Materials and methods

Experimental studies were carried out according to the method described in [4, 5, 19]. *ET* made of copper *M1* was chosen for experiments. The workpiece was made of *PCM* grade *VKU-39*. The workpiece was processed on a copy-piercing electrical discharge machine *Smart CNC* at a constant voltage $U = 50$ V, pulse on time $T_{on} = 100$ µs and current $I = 10$ A [4, 5, 19].

ANSYS CFX 20.1 software was used for theoretical flow simulation. Transformer oil (*Engineer oil*) was chosen to calculate the main flow directions and velocity distribution in the interelectrode gap. The oil temperature was set as standard, equal to 25 ^{o}C. For all cases, the pressure was 2.1 kg/cm^2 = 0.205 MPa. Flows distribution simulation was carried out at three values of the processing depth (2 mm, 10 mm, 15 mm), as well as at three values of the inclination angle of the nozzles (15°, 45°, 75°) (Figure 2–4).

The purpose of the simulation was to obtain a theoretical model for the distribution of working fluid flows in the processing zone, subjected to a change in the angle of flushing. To achieve a given purpose in the work, it is necessary to build the geometry of the region of computation; set the boundary conditions of the computation model, compute the model for the processing depth of 2 mm, 10 mm, 15 mm and the location of the nozzles 15˚, 45˚ and 75˚ relative to the tool axis (Figure 5).

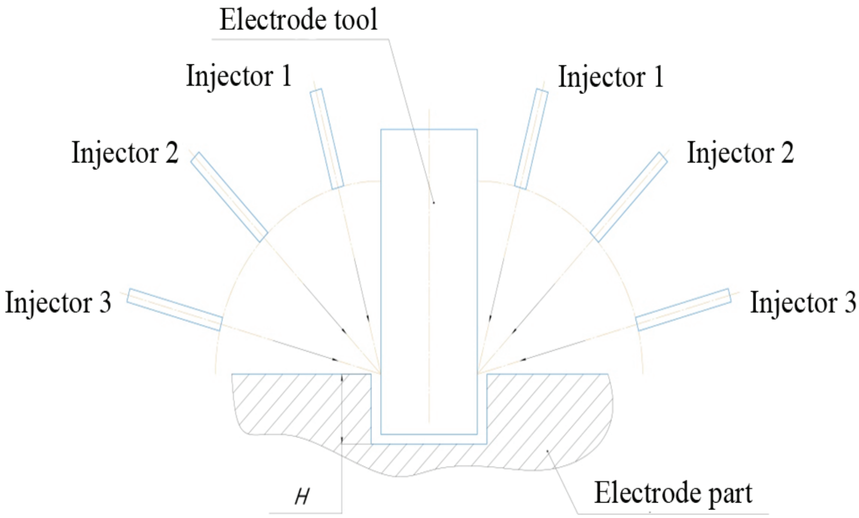


Fig. 5. Processing model, where *H* is the depth of processing

The experimental part, carried out in works [4–6], showed that products made of *PCM* during *EDM* are prone to sludge fusing on the processed surface. This is due to the irrational location of the flushing nozzles and the formation of turbulence in the processing zone.

Simulation was performed after specifying the names of the boundary surfaces: part walls, *ET* and flush nozzles. Geometry limits were similar for 10 mm and 15 mm processing, however, only the angle of the nozzles changed (Figure 6).

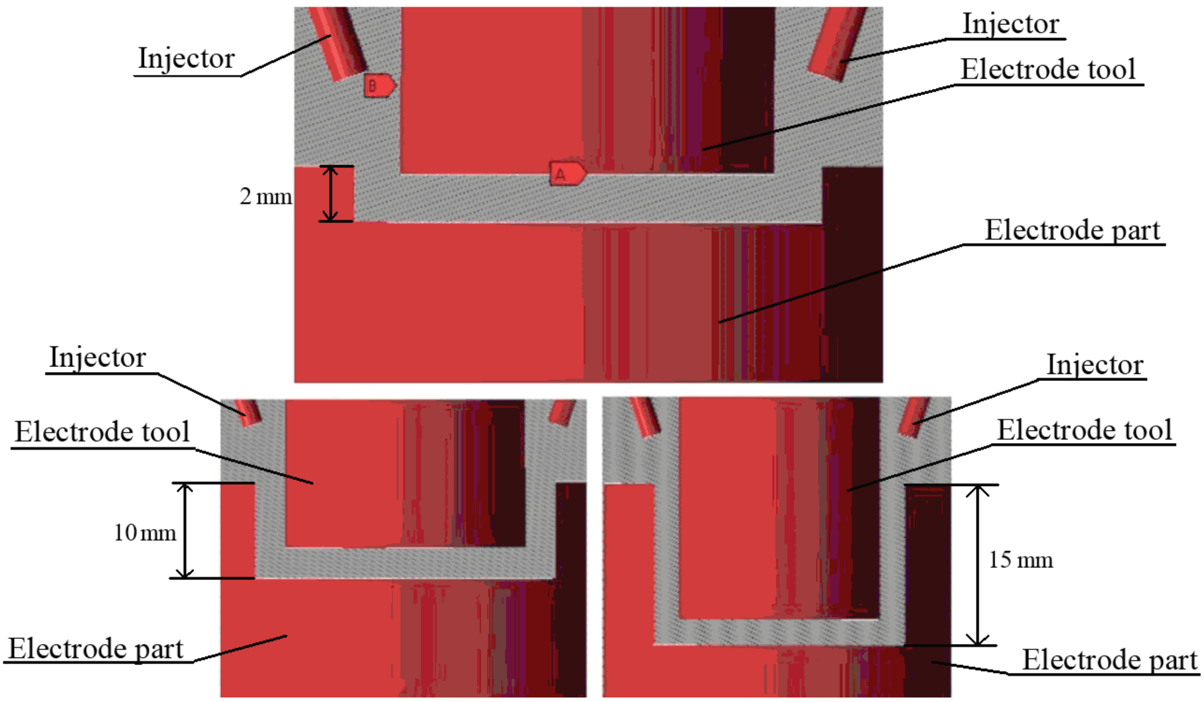


Fig. 6. Setting geometrical limits

The computational grid is shown in Figure 7. The minimum and maximum values of a single voxel were set to build the grid: min – 1 mm, max – 5 mm. The same conditions were set for other calculated cases. When modeling, it was assumed that the nozzles would operate at the same pressure and angle relative to the tool axis. For all cases, the pressure was identical and equal to 2.1 kg/cm^2 = 0.205 MPa.

It is shown that in the processing zone and boundary areas, the grid has taken the minimum values, which should have increased the simulation accuracy. The single-phase oil working fluid flow was modeled using the standard turbulence model (Figure 8).

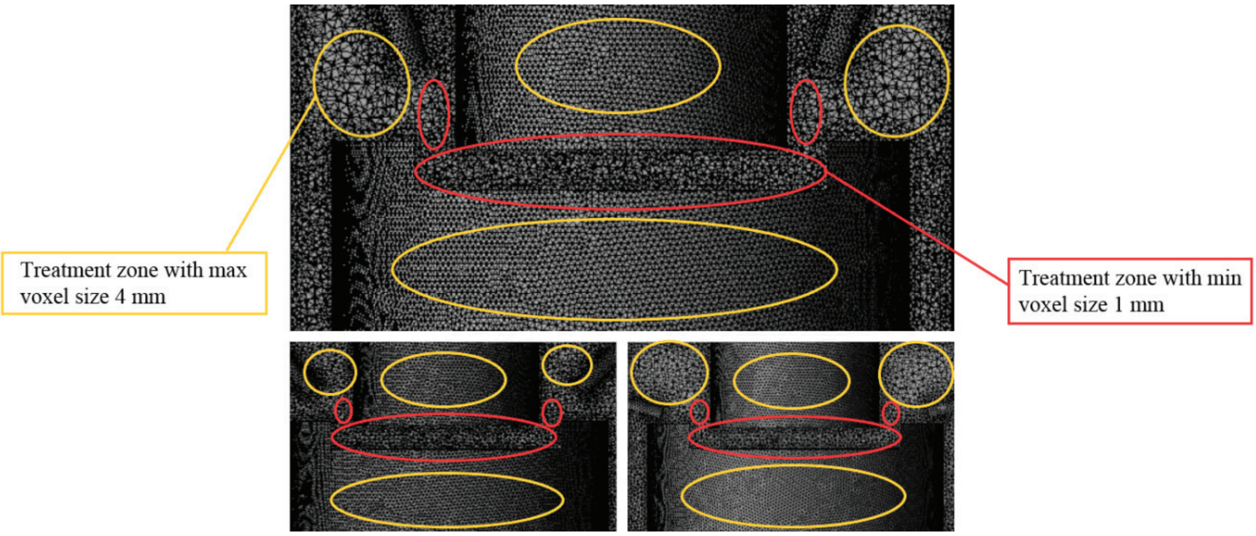


Fig. 7. Mesh model for calculation

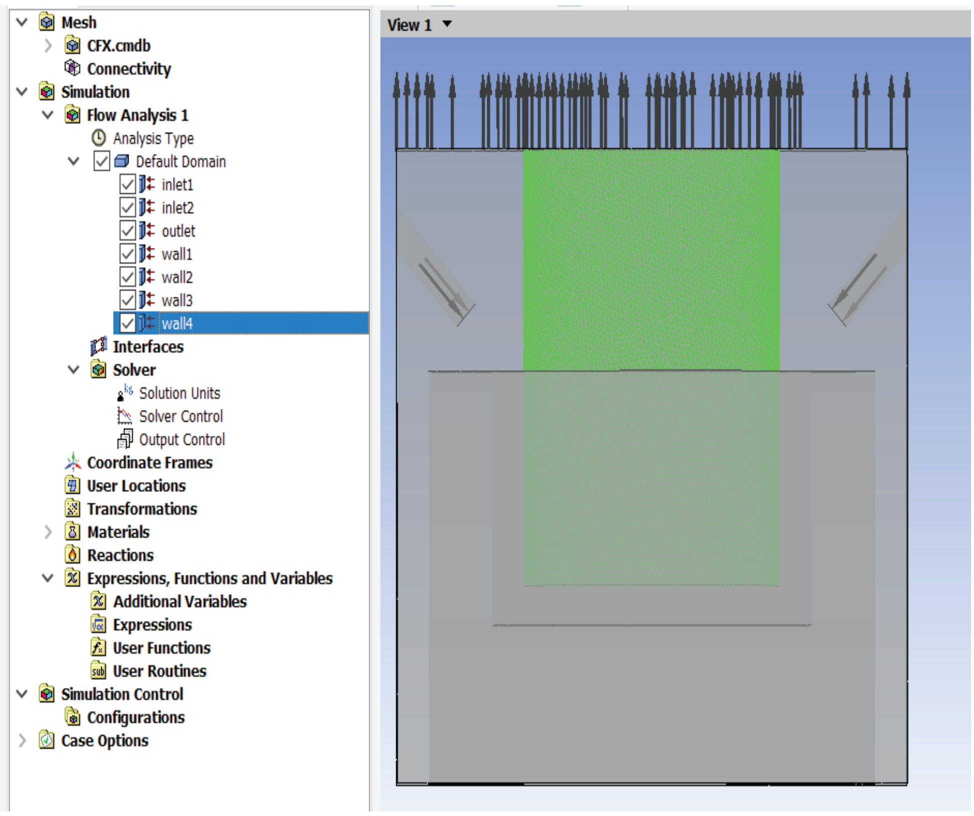


Fig. 8. Calculation construction tree with the final model of the *CFXPRE* module

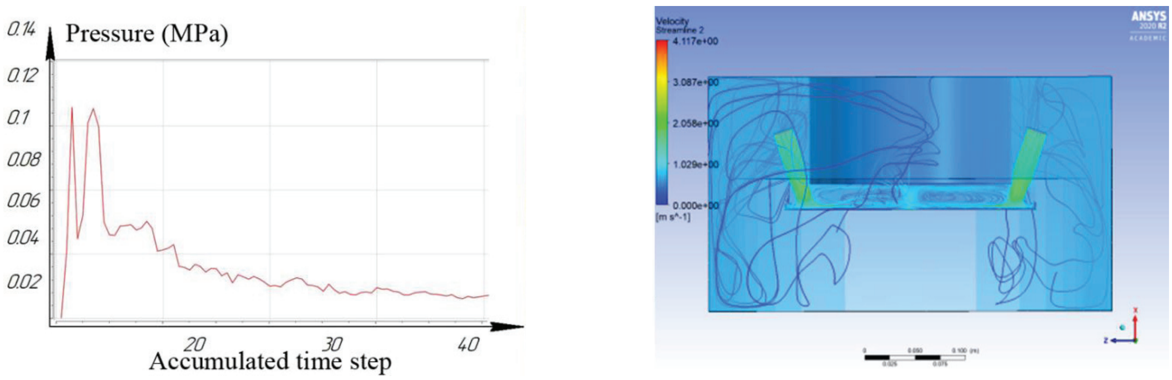
Oil flow geometry was collected using an enlarged image of the electrode cross section and simplified to reduce computation time. The number of elements of the tetrahedral grid varied from $7.8 \cdot 10^6$ to $6.4 \cdot 10^6$ in the hole of the workpiece according to the geometry of the volumetric flow due to small geometric features within the processing zone. Calculations were carried out in the *Ansis Fluid Flow* module.

Results and discussion

Based on the data obtained, it is found that the influence of the nozzles angle on the flushing efficiency is not significant when processing a *PCM* sample to a depth of 2 mm. Figures 9–11 show that the laminar flow of the fluid predominates.

With a processing depth of 10 mm, it is found that the laminar movement of the working fluid prevails for the nozzle located at an angle of 15˚. Turbulence is formed in the processing zone. The flows of 2 nozzles collide in this zone. It is noted that for nozzles located at angles of 45˚ and 75˚ turbulence is formed in the interelectrode gap and entails a slight decrease in pressure. Sludge removal from the processing zone is difficult (Figures 12–14).

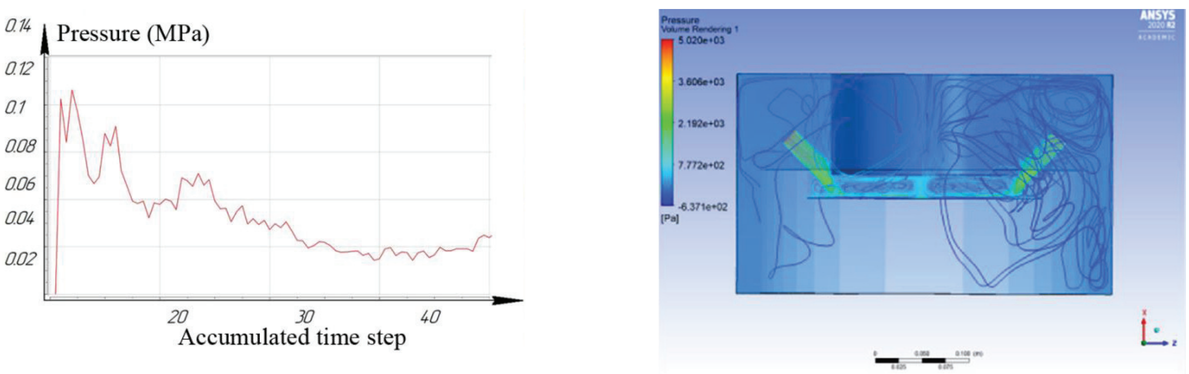
Figures 15–17 show that at a working depth of 15 mm for a nozzle located at an angle of 15˚, the laminar movement abruptly turns into turbulent. In the processing zone, the flows of the two nozzles collide. Turbulent motion dominates completely. It is established that when processing holes of a given depth and above, the location of the nozzles at an angle of 45˚ and 75˚ relative to the tool axis is inappropriate. This is caused by high flow turbulence and loss of transformer oil pressure in the processing zone (Figures 15–17).



a *b*

Fig. 9. Depth 2 mm, nozzle angle 15°:

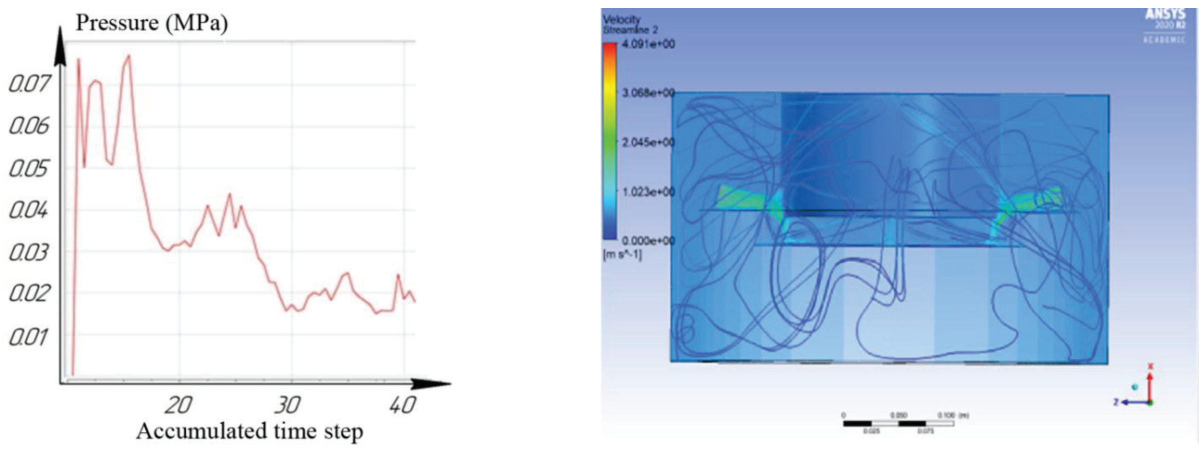
a – computation of the pressure of the working fluid; *b* – flow distribution models



a *b*

Fig. 10. Depth 2 mm, nozzle angle 45°:

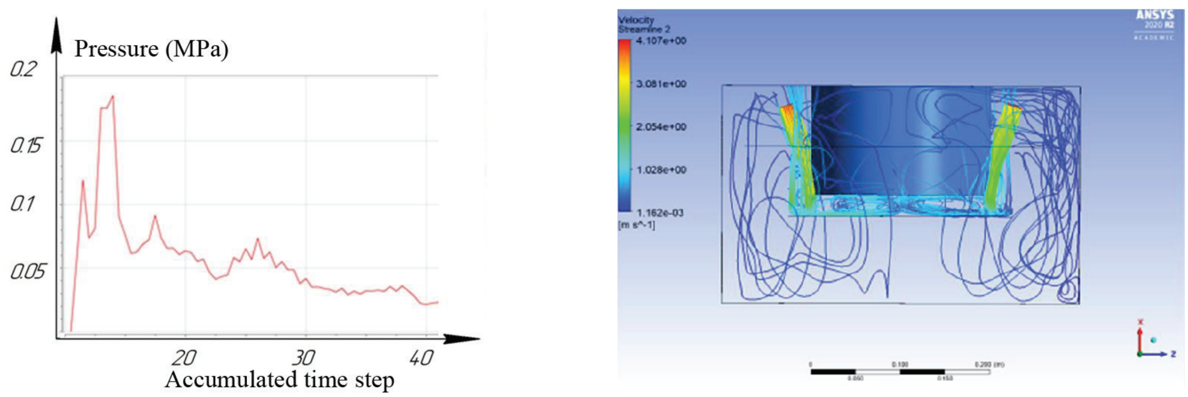
a – computation of the pressure of the working fluid; *b* – flow distribution models



a *b*

Fig. 11. Depth 2 mm, nozzle angle 75°:

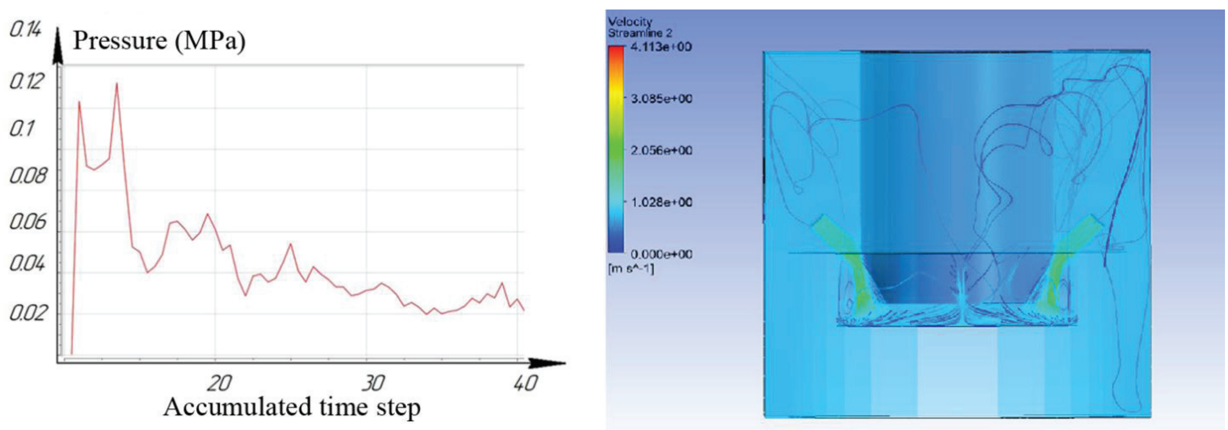
a – computation of the pressure of the working fluid; *b* – flow distribution models



a *b*

Fig. 12. Depth 10 mm, nozzle angle 15°:

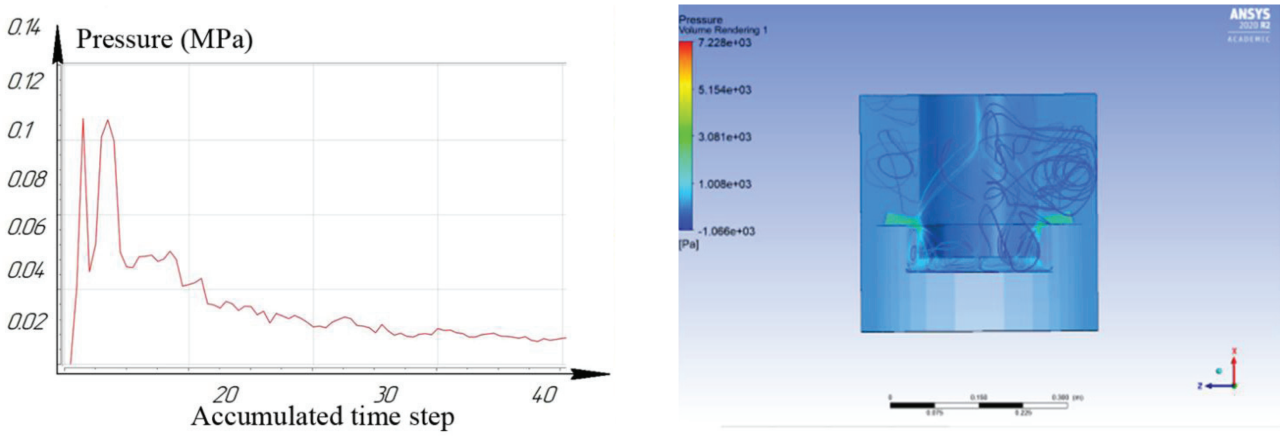
a – computation of the pressure of the working fluid; *b* – flow distribution models



a *b*

Fig. 13. Depth 10 mm, nozzle angle 45°:

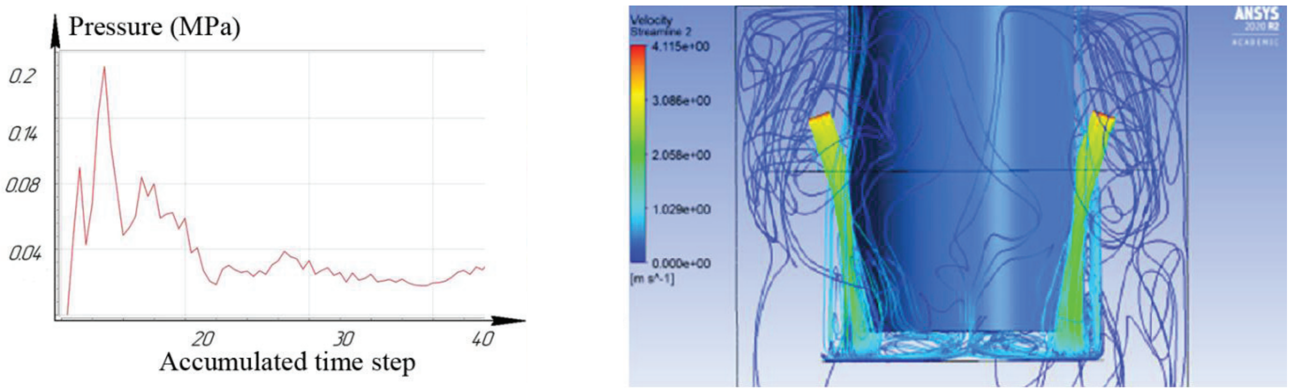
a – computation of the pressure of the working fluid; *b* – flow distribution models



a *b*

Fig. 14. Depth 10 mm, nozzle angle 75°:

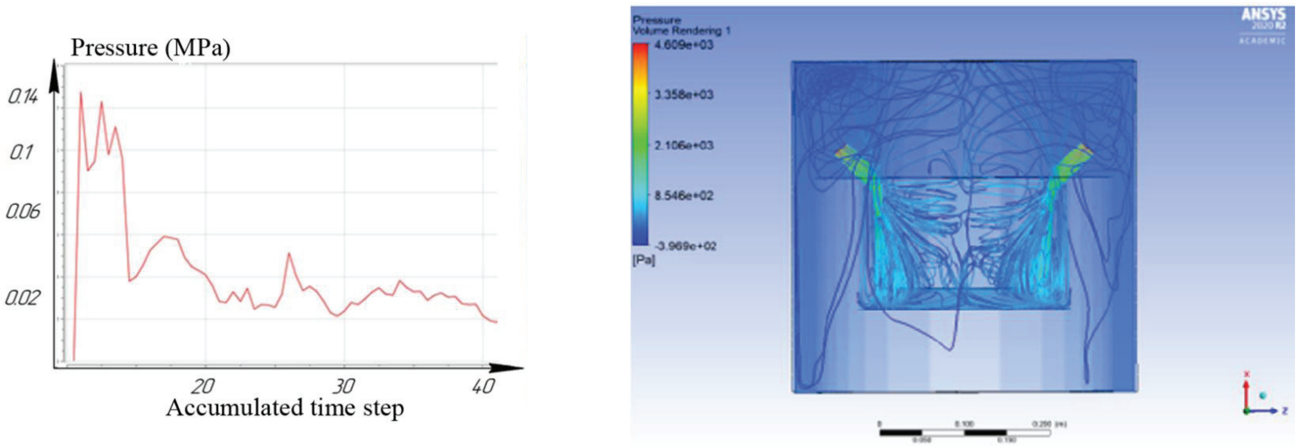
a – computation of the pressure of the working fluid; *b* – flow distribution models



a *b*

Fig. 15. Depth 15 mm, nozzle angle 15°:

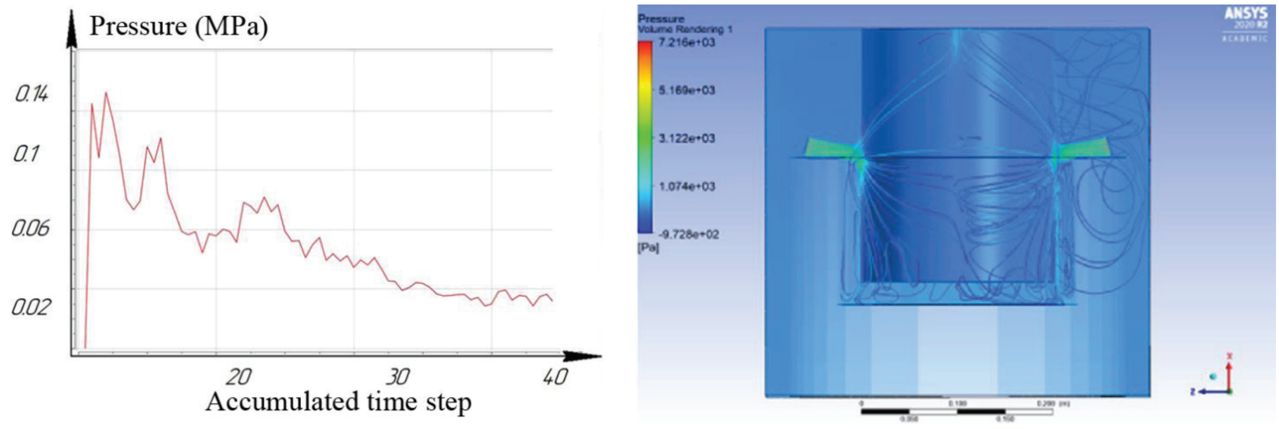
a – computation of the pressure of the working fluid; *b* – flow distribution models



a *b*

Fig. 16. Depth 15 mm, nozzle angle 45°:

a – computation of the pressure of the working fluid; *b* – flow distribution models



a *b*

Fig. 17. Depth 15 mm, nozzle angle 75°:
a – computation of the pressure of the working fluid; *b* – flow distribution models

From the presented figures, it can be concluded that when the nozzles are located at 45˚ and 75˚, the turbulent movement prevails. This entails a reduction in pressure. The pressure value for the nozzle at 75˚ does not exceed 0.07 MPa, while the nozzle at 15˚ provides a rational pressure in the processing zone from 0.1 MPa to 0.2 MPa.

It is shown that the location of the nozzle at 75˚ for processing holes deeper than 10 mm reduces the pressure in the processing zone by 2 times. For processing holes deeper than 15 mm, the location of the nozzles at 75˚ critically affects the pressure and speed of the working fluid, and the time of evacuation of eroded particles from the processing zone. This negatively impacts performance.

To clarify the theoretical computation, experimental studies were carried out to measure the performance of the *EDM* of *PCM* products (Figure 18).

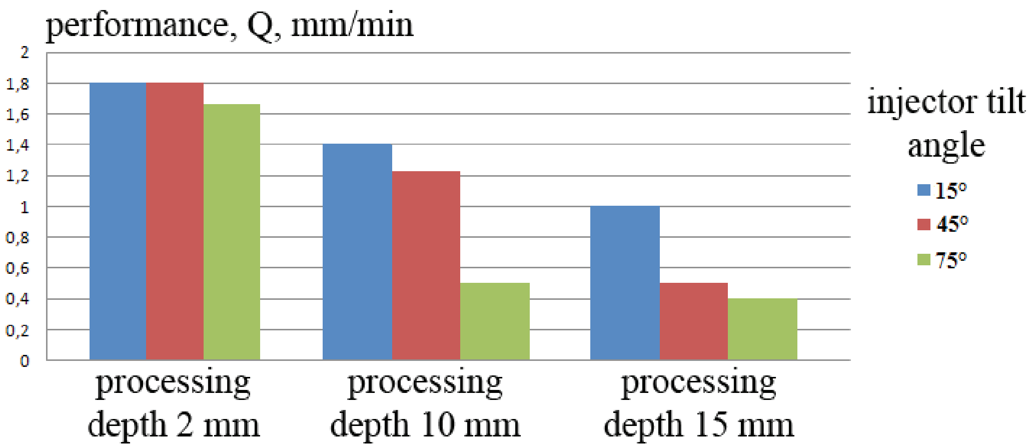


Fig. 18. Performance values

It is shown that when processing holes with a depth of 2 mm, the value of the flushing nozzle angle of inclination does not affect the performance of the *EDM*.

The effect of the influence of the nozzles inclination angle is manifested during the *EDM* to a depth of 10 and 15 mm. A decrease in the value of the productivity of the process of *EDM* is observed due to the difficulty in flushing the interelectrode space from sludge. The angle of the flushing nozzle inclination should be taken into account for processing holes with a depth of 10 mm or more. For effective processing, eroded particles should be removed from the gap. During the experimental study, when processing holes with a depth of 15 mm, sticking of sludge to the *ET* is observed, as well as the closure of the *EDM* process, the occurrence of secondary discharges in the processing zone, which caused the processing to stop. The obtained experimental data confirm the results of theoretical computation.

Conclusion

1. A theoretical model is obtained. This model describes the process of flushing the *EDM* zone for different depths of processing and the location of the nozzles for supplying the working fluid.

2. It is established that at a processing depth of 2 mm, the location of the nozzles does not affect the quality of flushing and the performance of the *EDM* of *PCM* grade *VKU-39*. The laminar flow of the fluid predominates.

3. It is shown that when the *EDM* of *PCM* grade *VKU*-39 to a depth of 10 mm and 15 mm, the location of the nozzles affects the quality of flushing and the performance of processing. The highest performance value is achieved when the nozzles are located at an angle of 15˚. For processing holes with a depth of 10 mm or more, the angle of flushing nozzle inclination should be taken into account. For effective processing, eroded particles should be removed from the processing zone. When processing at angles of 45˚ and 75˚, turbulent fluid flow occurs. Also, the possibility of secondary discharges arises. The sticking of sludge on the surface of the *ET* and the occurrence of a short circuit are experimentally confirmed. This leads to the instability of the process of *EDM* of products from *PCM* grade *VKU-39*. For holes with a depth of 15 mm, the location of the nozzles at 75˚ critically affects the pressure, speed of the working fluid and the evacuation of eroded particles from the processing zone. This reduces performance.

4. The conducted experimental studies show the efficiency of the obtained theoretical model. It is established that when processing blind holes with a depth of about 15 mm, it is necessary to set the nozzle angle to 15˚. With this arrangement of nozzles, the liquid pressure values and the sludge output are stable. This ensures the highest productivity in the case of deep hole *EDM* in products made from *PCM* grade *VKU-39*.

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Conflicts of Interest

The authors declare no conflict of interest.