

## Analytical Determination of the Productivity of a Vibrating Machine for Cleaning Parts Contamination with a Submersed Pulsating Two-Phase Flow of Liquid

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### ABSTRACT

The work presents an innovative design of a vibrating machine for cleaning pollution with a pulsating immersed jet with solid particles and analytically obtained the dependence of the mass productivity of the machine on the design parameters of the machine and the modes of operation of the vibration drive. The research results show that the optimal oscillation frequency of the machine drive lies in the range from 13 to 14 Hz with an amplitude of oscillations of 2 mm and a ratio of the diameter of the nozzle to the diameter of the pulsation chamber of 1:10. The conducted studies of the effectiveness of cleaning showed that mass wear of metal balls and changes in the roughness of the base of the sample is practically not observed due to the occurrence of minor stresses on the surface of the sample elastic character. As a result of the study of the efficiency of cleaning model pollution, it was found that increasing the angle of attack of a pulsating immersed jet with metal balls from 90° to 125° leads to an increase in the efficiency of cleaning. The analysis of the appearance of the surface structure of the model pollution during the cleaning process confirmed the main theoretical assumptions about the mechanical nature of the interaction of the immersed pulsating flow of the washing liquid with solid particles and pollution.

**Keywords:** vibration machine, performance, pulsating submerged jet.

### INTRODUCTION

In the process of manufacturing parts and assemblies, the operation of machines and equipment, technological and operational pollution is formed on their surface. During maintenance and repair, it is necessary to clean and wash the

parts before assembling them into assemblies. To achieve high-quality cleaning from pollution, a complex physicochemical and mechanical effect is used: the use of chemical substances that dissolve pollution, and the mechanical energy of the environment and other means (scrapers, brushes, liquid jets, abrasive jets) or

solid particles). Widespread special equipment is made for washing and cleaning parts, but in the conditions of small-scale production the purchase of expensive equipment for the repair of equipment becomes impractical. Depending on the type of surface contamination of parts and their purpose, the following cleaning and washing methods are used: ultrasonic [1-3], jet [4-7], abrasive-jet [8-11], shot-jet [4, 12-14], vibrating with an abrasive filler [15-16], submerged jets with an abrasive or balls [4, 17-18].

Many researchers have dealt with issues of the theory and practice of cleaning and washing parts [15, 19-22], but with the improvement of the technological processes of manufacturing parts, with the increase of technical requirements for the quality of repair of equipment objects, the task of finding new technologies and methods of cleaning and washing objects arises, especially in small series and single types of production.

Leading scientists were engaged in the development of theoretical foundations and modeling of the processes of interaction of solid particles with the surface [8, 23-25]. The behavior of particles in flows after collision with a flat surface has been studied [26-27], numerical modeling of the cleaning of steel parts from rust using blast-jet processing [28] has been carried out, models of surface evolution during abrasive-jet processing [28] have been created using the method of discrete elements, particle impact velocities in fluidized granular flows were determined [18, 23], characteristics of abrasive slurry jet processing in comparison with abrasive air-jet processing were determined [25].

The authors [28-30] investigated and carried out numerical modulation of the processes of cleaning the surfaces of parts using shot-jet and determined the influence of the main factors on the process of cleaning surfaces from contamination.

Increasing the efficiency of jet cleaning machines is achieved by increasing the impact of the pulsating submerged jet on the contaminated surface due to the introduction of solid particles into the liquid stream [18, 31, 32]. High-quality cleaning from pollution is achieved by increasing the normal and tangential frictional forces of the flow.

The purpose of the work is the analytical determination of the influence of the geometric parameters of the vibrating machine and the characteristics of the vibratory drive on the cleaning performance.

## METHODS AND CALCULATIONS

After analyzing the results of the author's research [4], it was established that the performance of the cleaning process depends on many factors that are entered in formula (1), but the dominant one is the flow rate of liquid with solid particles. The amount of material  $G_{\Sigma}$  removal with processing time, depending on various factors, is determined according to the dependence:

$$G_{\Sigma} = \frac{\pi \cdot k \cdot k_v \cdot \alpha \cdot Q \cdot \rho_1 \cdot \rho_2 \cdot D \cdot V_p^3 \cdot L^2 \cdot \text{tg}^2 \beta (1 - k_g) \cdot t}{2 \cdot H_{din.h}} \quad (1)$$

where:  $k$  – is the coefficient that characterizes the type of wear;

$k_v = 0.121$  – dimensionless coefficient;

$\alpha$  – coefficient that takes into account the space between particles;

$Q$  – concentration of particles in a unit volume of suspension;

$\rho_1, \rho_2$  – material density of particles and details;

$D$  – characteristic particle size;

$V_p$  – particle impact speed on the surface;

$L$  – jet length;

$H_{din.h}$  – dynamic hardness of the material according to Mayer;

$\beta$  – the angle of inclination of the outer boundaries of the jet to its axis;

$t$  – processing time;

$k_g$  – is the coefficient of gas content of the jet.

The author [13] based on the analysis of dependence (1), gives the calculated dependence of the mass productivity of the process of cutting material with solid particles, taking into account the increase in efficiency due to the increase in the kinetic energy of the particle and the decrease in the conditional cutting stress, and depending on the distance from the cut of the jet nozzle to the surface being processed.

$$G_{\Sigma} = \frac{k_0 \cdot m_p \cdot V_p^3}{4 \cdot \sigma \cdot H} \quad (2)$$

where:  $k_0$  – is the number of abrasive grains that take part in the processing process;

$m_p$  – particle mass;

$V_p$  – speed of particle impact on the surface;

$\sigma$  – conditional stress of material cutting (energy intensity of processing) [12];

$H$  – the distance from the nozzle cut to the surface to be cleaned.

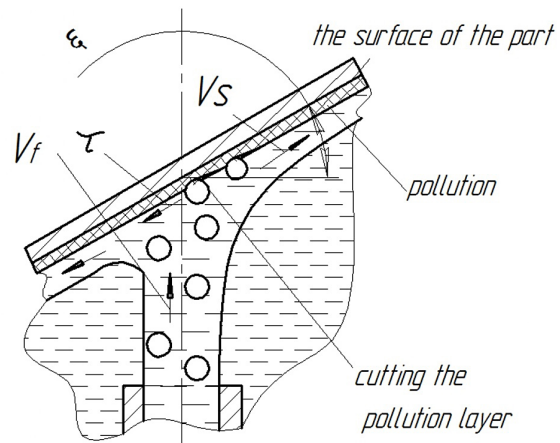
It was established that the speed of the submerged pulsating jet from the nozzle can vary depending on the design parameters of the pulsation chamber and the vibration modes of the drive, namely, the frequency and amplitude of the oscillations. Also, the speed of the jet decreases with increasing distance from the nozzle cut to the surface to be cleaned. Therefore, it is important to consider these factors to analytically determine the performance of a vibrating machine. After conducting an analysis of the nature of contamination that occurs on the parts, as well as based on the analysis of the results of experimental studies, the operating parameters of the machine drive and its design features are determined.

Taking into account the physicochemical factors of the cleaning medium, it is believed that the process of mechanical impact of liquid with solid particles on pollution is the main factor that determines the performance of cleaning. In general, the process of cleaning pollution with a submerged flow of liquid with solid particles can be divided into the following processes: the creation of a pulsating submerged jet of liquid with solid particles, the cyclic impact of the liquid flow on the surface, detachment of elements of pollution with solid particles and washing from the surface being cleaned, suspension of pollution particles in the liquid in the tub for washing, washing away dirt to the filter device.

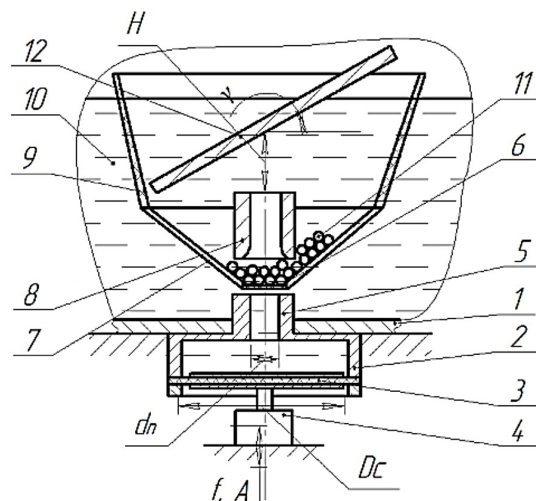
When cleaning pollution with the mechanical effect of a submerged flow of liquid with solid particles on the pollution, the inertial forces of solid particles also begin to act, which creates micro-cutting processes and increases normal and tangential stresses in the pollution layer, displacing the pollution. As is known [17, 31], the highest productivity of the cleaning process is characterized by the maximum pressure value of the pulsating jet (or speed) on the surface being washed, the degree of its turbulence, and the productivity of the cleaning process depends on both the maximum pressure of the pulsating jet, as well as from the number and mass characteristics of solid particles ejected by the nozzle. Figure 1 shows the scheme of the interaction of a submerged jet of liquid with solid particles with a contaminated surface, proposed by the authors.

The design of vibration machines proposed by the authors in the publication [18] contains bath 1 for cleaning contamination with a dipped pulp jet of solid particles, vibration drive 4, pulsation

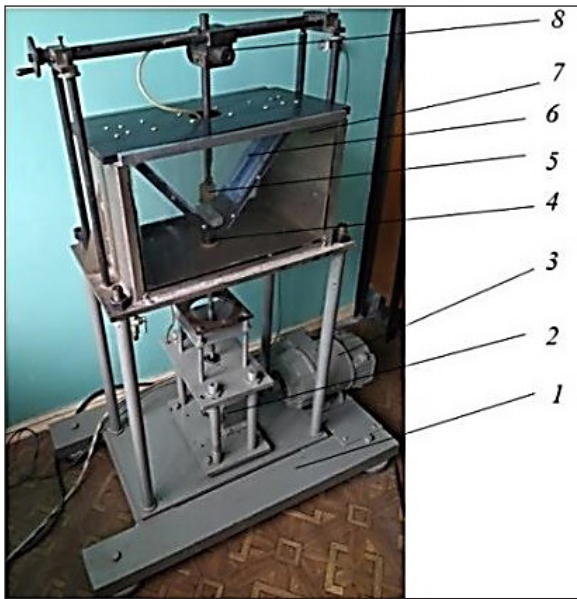
chamber 2, ejection knot containing nozzles 5, mesh 6 and nozzle 8. Creating a pulsating stream is obtained by a pulsation chamber with a nozzle when operating the drive of machine 4 according to the scheme (Fig. 2), proposed by the authors.



**Fig. 1.** Scheme of the interaction of a submerged two-phase flow of liquid with solid particles with a contaminated surface:  $V_f$  – rate of liquid with solid particles at the exit of the nozzle;  $\tau$  – frictional force of liquid flow with particles;  $\xi$  – is the angle of inclination of the surface of the part with contamination;  $V_s$  – is the speed of liquid spreading over the surface



**Fig. 2.** Scheme of operation of a vibrating machine for cleaning machine parts in a pulsating submerged two-phase flow of liquid with solid particles: 1 – bath; 2 – oscillating capacitance; 3 – membrane with discs; 4 – drive; 5 – nozzle; 6 – grid; 7 – box for solid particles; 8 – nozzle; 9 – grid; 10 – washing liquid; 11 – solid particles; 12 – surface to be cleaned;  $H$  – is the distance from the nozzle cut to the surface to be cleaned;  $d_n$  – nozzle diameter;  $D_c$  – is the diameter of the oscillating capacitance;  $f$  – frequency of oscillations of the drive;  $A$  – is the amplitude of drive oscillations (author's development [18])



**Fig. 3.** An experimental vibrating machine: 1 – base; 2 – vibration drive; 3 – direct current electric motor; 4 – nozzle; 5 – pressure sensor; 6 – container; 7 – bath; 8 – mechanism for moving the sensor (author’s development)

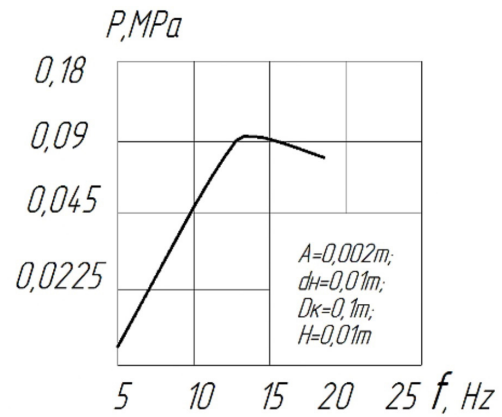
Figure 3 shows a research-experimental vibration machine for cleaning contamination (liquid is not flooded), made by the authors.

The search for optimal modes of operation of the drive of the vibrating machine was carried out experimentally by measuring the change in the maximum pressure of the jet from the nozzle during the oscillation cycle of the drive.

To determine the nature of the change in the maximum speed of the immersed liquid jet, when the operating parameters of the vibration drive are changed, it was proposed to measure the maximum pulsating pressure of the jet on the nozzle section during the drive oscillation cycle, which gives an equivalent picture from the point of view of the physical process.

For this purpose, in the initial section of the flooded pulsating jet at a distance of 10 mm from the section of the nozzle in the experimental setup of Figure 3, a membrane pressure sensor based on strain gauges is installed. In the study, the maximum pressure of the jet during the period of oscillation of the immersed pulsating jet was determined and recorded in the form of oscillograms. After their processing, a graph of the dependence of the maximum value of the pressure from the nozzle on the change in the frequency of oscillations was plotted in Figure 4.

From the graph of Figure 4, it is established that the maximum values of liquid pressure



**Fig. 4.** Graph of the dependence of the maximum pressure of the immersed pulsating jet with a change in the frequency of oscillations

on the section from the nozzle as a function of frequency, starting with frequencies of 13–14 Hz, the maximum pressure of the pulsating jet decreases due to the appearance in the pulsation chamber of a significant number of cavitation bubbles filled with gas, which play the role of an elastic element [18].

Accordingly, in the range of frequencies from 13 to 14 Hz, the pulsating submerged jet from the nozzle has the maximum speed, as well as the maximum cleaning performance. For a vibrating pollution cleaning machine, taking into account that the speed of the particle is equal to the speed of the jet, you can write down a new expression for calculating the mass productivity, taking into account the frequency and amplitude of vibration of the vibration drive in the following form:

$$G_{\Sigma} = \frac{k_0 \cdot m_u \cdot (A_n \cdot f)^3}{4 \cdot \sigma \cdot H} t \quad (3)$$

where:  $A_n$  – is the amplitude of liquid oscillations in the nozzle;

$f$  – is the vibration frequency of the vibration machine drive.

Taking into account the continuity of the flow of liquid between the pulsation chamber and the nozzle  $A_c \cdot S_c = A_n \cdot S_n$ , for the maximum speed of the liquid at the outlet of the nozzle  $V_{p,max}$ , we write the following dependence:

$$V_{p,max} = \frac{\varepsilon \cdot D_c^2 \cdot A_c \cdot f}{d_n^2} \quad (4)$$

where:  $A_c$  – is the amplitude of liquid oscillations in the pulsation chamber;

$\varepsilon$  – coefficient of narrowing of the flow in the nozzle;



$D_c$  – the diameter of the pulsation chamber;  
 $d_n$  – nozzle diameter;  
 $f$  – is the vibration frequency of the vibration machine drive.

Let's take into account the change in the speed of the liquid with the increase in the distance from the nozzle-ejector cut to the surface to be cleaned. On the Hs segment, the velocity of the jet from the ejector nozzle changes as a function [19]:

$$V_p = \frac{0.645 \cdot V_{p,0}}{1 + \frac{2H}{D_n} \operatorname{tg}\alpha} \quad (5)$$

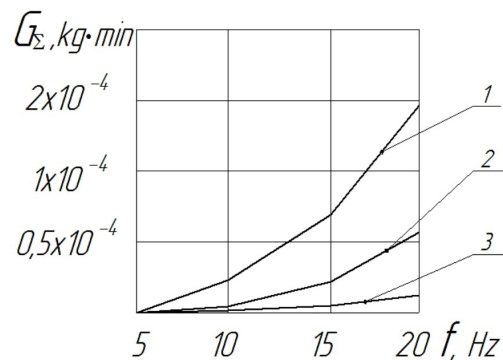
where:  $V_{p,0}$  – is the initial speed of the flow of liquid and particles from the nozzle;  
 $D_n$  – nozzle diameter;  
 $H$  – is the distance of the jet from the nozzle section to the surface to be cleaned;  
 $\alpha$  – the angle of one-sided expansion of the jet from the nozzle,  $\alpha = 12^\circ 40'$ .

From the analysis of dependencies (3) and (5), it can be concluded that the performance of the cleaning process is affected by the number of particles in the jet and their mass at the smallest distance from the nozzle cut to the surface to be cleaned in the presence of the smallest pollution shear stresses.

It was established that the main parameter that affects productivity is the flow rate, which has the third power in formula (3) and a slight increase in speed leads to a significant increase in productivity. The main factor that affects the performance of the process is the speed of the particle, which has the third power in formula (3) and its slight increase leads to a significant increase in productivity.

From the analysis of the physical picture of the process, we enter the shear modulus  $\mu$  into formula (6) as a more likely alternative to the conditional cutting stress of the material  $\sigma$ , which the author [13] does not explain why it is equal to.

Taking into account the change in the initial value of the velocity and particles at the exit of the pulsating jet of liquid from the nozzle from the distance to the surface (5) being cleaned and taking into account the design parameters of the pulsation chamber and operating modes of the vibration drive (4), it is possible to write down the following dependence proposed by the authors for determining the mass productivity of the vibration machine:



**Fig. 5.** The schedule for calculating the mass productivity of pollution cleaning with a flow of liquid with balls in a vibrating machine per minute: 1 – the amplitude of oscillations is 3 mm; 2 – amplitude of oscillations of 2 mm; 3 – oscillation amplitude of 1 mm;  $\mu = 2$  MPa

$$G_\Sigma = \frac{k_0 \cdot m_p \cdot \left( \frac{0.645 \frac{k_c \cdot \varepsilon \cdot D_c^2 \cdot A_c \cdot f}{d_n^2}}{1 + \frac{2 \cdot H}{D_n} \operatorname{tg}\alpha} \right)^3}{4 \cdot 10^6 \cdot \mu \cdot H} \quad (6)$$

where:  $k_0$  – is the number of particles that take part in the processing process;  
 $m_p$  – particle mass;  
 $\mu$  – shear modulus.

Based on the results of calculations in the MathCad software, the authors constructed graphs of the dependence of the mass productivity of pollution cleaning per minute, which are shown in Figure 5.

In theoretical calculations, it is not possible to predict the influence of all factors on the performance of a vibrating machine, therefore, an experimental study of the cleaning performance of a model pollution by an immersed pulsating jet with metal balls was carried out over time with a change in the angle of attack of the jet at the determined optimal parameters of vibrations of the vibration drive of the machine. The intensity of cleaning productivity was determined by the average relative decrease in the weight of the sample. The weight loss of the samples was determined by the difference in weight before and after treatment during the controlled time (2 min.) according to the formula:

$$\Delta_m = m_1 - m_2 \quad (7)$$

where:  $m_1$  – the weight of the sample before cleaning;  
 $m_2$  – the weight of the sample after cleaning.

Cleaning productivity was determined by the dependence:

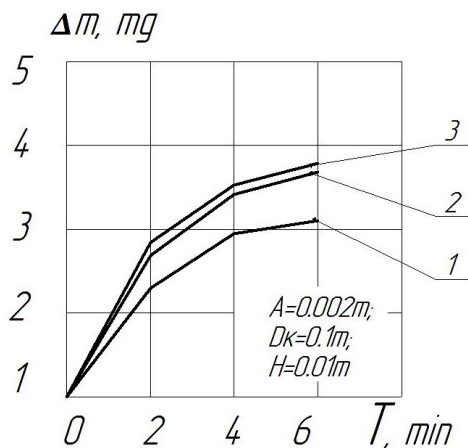
$$G = \Delta m(F, t) \quad (8)$$

where:  $\Delta m$  – the change in sample weight;  
 $(F, t)$  – the function of changing the weight of the sample over time.

## RESULTS

The results of the research are presented in the form of a graph in Figure 6, which shows the dependence of the cleaning productivity from the surface of the sample of model pollution on the processing time and with the change in the angle of attack of the pulsating immersed liquid jet with solid particles (metal balls 0.8 mm) of the surface to be cleaned. Mass wear of metal balls and change in the roughness of the base of the sample were practically not observed due to the occurrence of minor elastic stresses on the surface of the part.

As a result of the study of cleaning productivity of model pollution, it was established that increasing the angle of attack of a pulsating submerged jet with metal balls from 90° to 125° leads to an increase in cleaning productivity (the tangential stresses between the ball and the pollution begin to have a significant effect, leading to its more active disruption). A further increase in the angle leads to a slight increase in processing performance (the effect of normal stresses between the ball and the contamination begins to decrease).



**Fig. 6.** Graphs of cleaning performance from the surface of a sample of model pollution over time at different angles of a submerged jet with metal balls from the vertical axis of the jet to the surface: 1 – angle 90°; 2 – angle 125°; 3 – angle 135°

Rational processing modes were chosen for the drive of the vibrating machine: vibration frequency of the vibration drive 14 Hz, amplitude of oscillations 2 mm, nozzle diameter 10 mm with a chamber diameter of 100 mm, and distance to the nozzle cut 30 mm.

Figures 7 and 8 show photographs of samples obtained by the authors with model contamination after treatment with a pulsating submerged jet



**Fig. 7.** Photograph of the surface of the sample with model pollution after treatment with a pulsating jet of liquid with metal balls, angle 90° (scale 1:8)



**Fig. 8.** Photograph of the surface of the sample with model contamination after treatment with a pulsating jet of liquid with metal balls, angle 125° (scale 1:3)

of liquid with 0,8 mm metal balls at optimal treatment modes at different angles of inclination of the jet axis to the surface being cleaned. On the surface of the sample (Fig. 7), the result of the process of pressing the ball into the viscous contamination at an angle of 90° of the surface being cleaned and the subsequent displacement of the particle of contamination (Fig. 8) during the tangential movement of the ball in the flow of liquid along the surface of the contamination at an angle of 125° is observed surface to be cleaned.

## CONCLUSIONS

The obtained analytical dependence of the performance of the vibrating machine for cleaning pollution with a pulsating submerged jet of liquid with solid particles makes it possible to determine the influence of the operating modes of the drive and the design parameters of the pulsation chamber on the efficiency of the pollution cleaning process.

It was experimentally established that the optimal frequency of oscillation of the drive for cleaning lies in the range from 13 to 14 Hz with an oscillation amplitude of 2 mm and a ratio of the diameter of the nozzle to the diameter of the chamber of 1:10. The recommended range of angles of attack of a submerged pulsating liquid jet with solid particles to the surface is within 125–135°. The analysis of the appearance of the surface of model pollution confirmed the main theoretical assumptions of the mechanical nature of the interaction of a submerged pulsating jet of liquid with solid particles with pollution and showed the effectiveness of the method of cleaning pollution with a pulsating submerged jet of liquid with solid particles.

## REFERENCES

1. Chahine, G.L., Kapahi, A., Choi, J.-K., Hsiao, Ch.-T. Modeling of surface cleaning by cavitation bubble dynamics and collapse. *Ultrasonics Sonochemistry*, 29, (2016) 528-549.
2. Latyshenok, M. The main parameters of the abrasive-cavitation jet and their influence on the intensity of washing agricultural machines. *Herald of RGATU*, 4, (2010) 65–66.
3. Kohli, R. Mittal, Kashmiri L. Developments in Surface Contamination and Cleaning: Methods

- for Surface Cleaning. Volume 9. Elsevier, (2016) pp. 196.
4. Tsyganovsky, A. Technological possibilities of hydroabrasive processing with submerged jets. *Vibrations in engineering and technology*, 2, (2010) 205-215.
5. Burdick, G.M., Berman N.S., Beaudoin S.P. Hydrodynamic particle removal from surfaces. *Thin Solid Films*, 488, 1-2, (2005) 116–123.
6. Raykowski, A., Hader, M., Maragno, B. and Spelt, JX. Blast Cleaning of Gas Turbine Components: Deposit Removal and Substrate Deformation. *Wear*, 249, (2001) 127–132.
7. Witte, A.K., Bobal, M., David R., Blattler, B., Schoder, D., Rossmanith, P. Investigation of the potential of dry ice blasting for cleaning and disinfection in the food production environment. *LWT – Food Science and Technology*, 75, (2016) 735–741.
8. Ghobeity, A., Hailu, G., Krajac, T., Spelt, J.K. and Papini M. Process Repeatability in Abrasive Jet Micromachining. *J. Materials Processing Technology*, 190, (2007) 51–60.
9. Kowsari, K., Nouraei, H., James, D.F. Spelt, J.K. and Papini, M. Abrasive Slurry Jet Micro-machining of Holes in Brittle and Ductile Materials. *Journal of Materials Processing Technology*, 214, (2014) 1909-1920.
10. Nouhi, A., Kowsari, K., Spelt, J. K. and Papini, M. Abrasive Jet Machining of Channels on Highly-curved Glass and PMMA Surfaces. *Wear*, 356-357, (2016) 30–39.
11. Nouraei, H., Kowsari, K., Papini, M. and Spelt, J.K. Operating Parameters to Minimize Feature Size in Abrasive Slurry Jet Micro-machining. *Precision Eng.*, 44, (2016) 109–123.
12. Andilakhay, A. Abrasive processing of parts with submerged jets. *Mariupol. PGTU*, (2006) pp. 190.
13. Andilakhay, A. Conditions for increasing the productivity of abrasive processing. *Bulletin of NTU “KHPI”*, Xs 53(959), (2012) 42-47.
14. Karuppanan, S. Romero, J.S., de los Rios, E.R. et al. A theoretical and experimental investigation into the development of coverage in shot peening. In: Wagner IL (ed.) *Shot peening*. Weinheim: Wiley-VCH. (2002) pp. 101–107.
15. Zoeteweij, M.L., Van der Donck, J.C., Versluis, R. Particle removal in linear shear flow: model prediction and experimental validation. *Journal of adhesion science and technology*, 23, 6, (2009) 899–911.
16. Maieika, D., Ragulskis, K., Kandrotaitė-Janutiene, R., Bubulis, A., Bartkus, A. Cleaning of the surface contaminated by micro-particles by means of vibrations. *Vihroeng meeting Procedia*, 7, (2016) 65–69.
17. Ghobeity, A., Krajac, T., Buizynski, T., Papini, M. and Spelt, J.K. Surface Evolution Models in



- Abrasive Jet Micro machining. *Wear*. 264, (2007) 185-198.
18. Staryi, A. R., Hordeev, A. I. Research the impact on productivity of parameters and operating modes of the vibration machine drive for cleaning and washing contamination by submerget stream jet with sold particles. *East European Science Journal*. 1, 4(68), (2021) 46–52.
19. Abramovich, G.N., Girchovich, TA., Krasheninikov. S.Yu., Sekundov. A.N., and Smirnova, I.P. *Theory of Turbulent Jets*. Nauka. p.716, (1984).
20. Frija, M., Hassine, T., Fathallah, R . Bouraoui, C., Dogui, A. Finite element modelling of shot peening process: Prediction of the compressive residual stresses, the plastic deformations and the surface integrity. *Materials Science and Engineering*. 426, (2006) 173–180. DOI: 10.1016/j. nisca. 2006. 03.097.
21. Hiltimen, K., Jus berg, A., Kallio, S. *Multiphase Flow Dynamics. Theory and Numerics*. Helsinki: Edita Prima Oy. (2009) pp. 113.
22. Ciampini, D., Spelt, J. K., Papini, M. Simulation of interference effects in particle streams following impact with a flat surface. PartI. Theory and analysis. *Wear* 254, (2003) 237–249.
23. Ghobeity, A., Papini, M. and Spelt J.K. Abrasive Jet Micro-machining of Planar Areas and Transitional Slopes in Glass using Target Oscillation. *J. of Materials Processing Technology*, 209, (2009) 5123–5132.
24. Jafar, R. Haj, Mohammad, Spelt, J.K. and Papini, M. Numerical Simulation of Surface Roughness and Erosion Rate of Abrasive Jet Micro-machined Channels. *Wear*. 303, (2013) 302–312.
25. Hashemnia, K. and Spelt. J.K. Particle Impact Velocities in Vibrationally Fluidized Granular Flows Predicted Using the Discrete Element Method. *Chem. Eng. Sci.*, 109, (2014) 123-135.
26. Ciampini, D., Spelt J.K., Papini, M. Simulation of interference effects in particle streams following impact with a flat surface. *Pan Parametric study and implications for erosion testing and blast cleaning*. *Wear* 254, (2003) 250–264.
27. Nouraei, H., Wodoslawsky, A., Papini, M. and Spelt, J. K. Characteristics of Abrasive Slurry Jet Micro-machining: A Comparison with with Abrasive Air Jet Micro-machining. *J. of Materials Processing Technology*, 213, (2013) 1711–1724.
28. Li, Z., Yang, F., Liu, Y., Gao, Y. Numerical simulation of derusting treatment of steel parts by shot blast. *CMES-Computer Modeling in Engineering & Sciences*, 120, (2010) 157–175.
29. Chen, J., Desai, D., Heyns S., Pietra, F. Literature review of numerical simulation and optimization of the shot peening process. *Advances in mechanical engineering*. 11(3), (2019) 1–19.
30. Hong, T., Wen, D.H. and Yuan, J.L. Optimising shot peening parameters using finite element and discrete element analysis. *Appl Mech Mater*, 10-12, (2008) 493–497.
31. Pat. for utility model №132837. IPC B08B 3/10. Vibrating machine for cleaning contamination with a flow' of solid particles and washing parts during equipment repair. Skyba, M., Stary, A., Hordieiev, A., Hordieiev, O. u201810344; statement 19.10.2018. publ. 11.03.2019. Bui. (2019) 5.
32. Staryy, A.R., Hordieiev, A.I. Analysis of analytical models of the vibrating drive of the machine for washing and cleaning with a pulsating jet of liquid and experimental study of its modes of operation. *Herald of Khmelnytskyi National University, Technical Sciences*. 4. (2021) 77–83.
33. Cui, Y., Sommerfield, M. Forces on micron-sized particles randomly distributed on the surface of larger particles and possibility of detachment. *International Journal of Multiphase Flow*, 72, (2015) 39–52.