ISSN 1392–1207. MECHANIKA. 2014 Volume 20(2): 221–225

Simulation of concentration distribution of dispersed particles of magnetorheological fluid in the gap workpiece-tool of finishing polishing device

A. Mokeev*, E. Korobko*, A. Bubulis**
**Heat and Mass Transfer Institute of NAS Belarus, 15 P. Brovka str., 220072 Minsk, Belarus, E-mail: evkorobko@gmail.com*
***Kaunas University of Technology, 17, Donelaicio str, 44239, Kaunas, Lithuania, E-mail: algimantas.bubulis@ktu.lt*

crossref http://dx.doi.org/10.5755/j01.mech.20.2.6947

1. Introduction

Creation of a specialized opto-mechanical equipment for a high-quality surface finishing of optical and semiconductor workpieces, the parameters of which meet the modern requirements of aerospace and electronic equipment, is impossible to be based on technologies that use traditional mechanical lapping and polishing powders, containing only an abrasive component [1] and additionally a magnetically sensitive filler (magnetic abrasive treatment) [2]. The biggest problems arise in the production of aspheric optics, since it is necessary to use a large amount of polishing tools of various profiles. Furthermore, the direct application of the lapping method restricts the possibility of achieving high precision in surface shape not only because of wear and deformation of the polishing material, but also because of significant thermal deformation of the workpiece. For the implementation of a high-quality finishing surface treatment of special optical workpieces magnetorheological polishing method is used [3, 4], which is based on software-controlled tangential material removal by a magnetorheological polishing fluid (MRPF) jet, formed by the gradient magnetic field, with its local contact with the object of the treatment. In the magnetic field MRPF becomes a viscoplastic medium with controllable parameters and performs the function of the polishing tool. Magnetorheological polishing method allows one to obtain the lowest values of surface roughness of the processed samples of different materials. In particular, for workpieces made of space glass ceramics the achieved roughness was 2 Å [5].

Implementation of the technology cycle for operation of surface finishing of optical and semiconductor workpieces requires an iterative approach based on periodic monitoring object's shape with the help of special interferometers and control of critical values of roughness (surface finish) of a surface by measuring the integral index of its roughness, for example by means of atomic force microscopes. The comparison of controlled intermediate values of these parameters with the specified finite values of surface topology allows one purposefully make changes in PC controlled software for processing equipment.

Optimization of regime characteristics of the polishing process is based on the control (weight) of material removal from the workpiece surface, which depends on the pressing force of MRPF filler particles, the velocity of their tangential movements, the amount and distribution of them through the gap in the zone of the gradient magnetic field. Based on consideration of these parameters the most effective compositions of magnetorheological polishing fluids can be created.

2. Experimental part

Magnitoreological polishing fluid as the oncoming jet (Fig. 1), turning into a flat layer in the zone workpiece-tool, is used as a polishing tool. Similarly to simple lapping MRPF tool removes workpiece's surface roughness at a relative tangent movement of the workpiece - tool [4, 6].

Fig. 1 Image of the working area of the polishing device during finishing of the optical workpiece by a jet of MRPF

However, in the case of the jet stream MRPF top layer is pressed against the workpiece by appearing additional elasticity (Maxwell tension) in a gradient magnetic field of the jet MRPF complex filler contains magnetically sensitive particles (35 - 40% vol), of the size 5-10 μm, and the abrasive particles (cerium, aluminum oxides, nanodiamond powder and etc.) in an amount of 0.01 - 6%, vol. of the size 50 nm - 3 μm (Fig. 2).

Fig. 2 Image of abrasive particles structure (nanodiamond) for MRPF

In the area of magnetic impact in the treatment zone there is a division of the filler particles, magnetic particles are attracted to the substrate - tool, abrasive particles are gathered in the surface layer (Fig. 3).

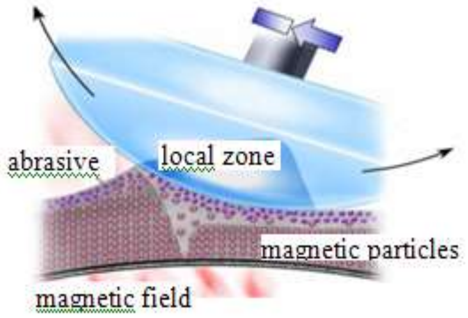

Fig. 3 Scheme of particles structuring for a complex filler of MRPF

Removal of material items is due to the cutting the surface roughness by sharp edges of abrasives moving with MRPF. It is believed that this process is due to collision of the workpiece surface with abrasive particles, due to the arising oscillations at their interaction with each other and the carrier medium in the granular flow (slurry) [7, 8].

The "soft" material removal with a jet stream allows to obtain currently the smallest surface roughness of high-quality optical workpieces. This effect is provided in contrast to traditional methods of polishing both by an optimal ratio of velocities of the workpiece - tool movement and the velocity of the MRPF jet flow, by the design of the magnetic system, which creates a magnetic field gradient, and compositional features of MRPF having the desired plastic characteristics and required complex filler particle distribution in the treatment zone.

3. Simulation and calculation

Let us consider MRPF flow in the gap workpiece - tool as a continuum in the approximation of lubrication theory. With a steady flow of MRPF any particle or aggregate of several particles moving with jet velocity V along its axis, sooner or later faces the other particle or aggregate with a relative velocity $V_r = \frac{d\ V\ z}{dz} d$, where d is sighting distance equal to the average diameter particles, dV / dz is shear rate. Particle collisions lead to the transfer of their average speed across their orderly movement the pulse (Fig. 4) of the value:

$$\Delta p = 2 p \sin\theta , \quad (1)$$

where θ is angle between the velocity vectors of the two particles.

Suppose if the initial sighting distance of the entire ensemble of particles are randomly distributed due to the occurrence of oscillations in a carrier medium, then the transferred pulse value by them is also random. Average MRPF velocity $V(z)$ profile is created [9] having effective temperature T_e. The average energy of motion of a single particle with velocity v is equal to $E_m = mv^2 / 2$.

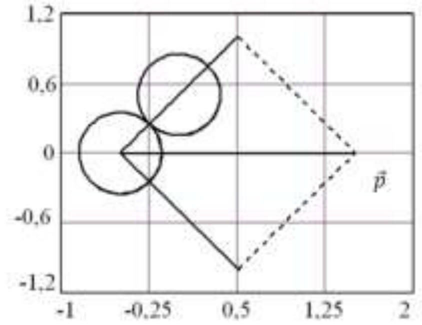

Fig. 4 Scheme of the pulse transfer at collision of two particles

The force of viscous friction F_T of elementary layer of MRPF (assuming the thickness corresponds to the particle diameter $d = 10^{-7}$ m) in the jet of MRPF can be written as:

$$F_T = -\frac{dp}{dt} = -\eta \frac{d\left(V(z)\right)}{z} S . \quad (2)$$

Work of this force during the relaxation time t_r is equal to the energy loss of the ordered motion:

$$\Delta E = E - E_0 = -\int F_T V_r dt = -F_T V_r t_r - E_0 , \quad (3)$$

where $V_r = \frac{d\left(V(z)\right)}{dz} d$ is relative velocity of flow layers, E_0 is initial energy.

It increases the energy that is homogeneously distributed along all particles of the layer, which determines the average velocity of motion inversely proportional to the concentration of the particles. The energy of ordered motion is converted into thermal energy in the volume $S \cdot d$, and could be expressed in terms of effective temperature and average velocity of motion v:

$$E = -nSd \frac{mv^2}{2} ; \quad E = -\frac{3}{2} nSdkT_e ; \quad T_e = \frac{mv^2}{3k} , \quad (4)$$

where n is volume concentration of the particles.

Considering relaxation one gets:

$$\left. \begin{aligned} & E = -F_T V_r t_r = -S\eta \frac{d\left(V(z)\right)}{dz} V_r t_r = -\eta t_r S \left(\frac{dV}{dz}\right)^2 d ; \\ & v^2 = \frac{2\eta t_r}{nm} \left(\frac{dV}{dz}\right)^2 . \end{aligned} \right\} , \quad (5)$$

Effective local temperature with consideration of Eq. (4) is equal to:

$$T_e = \frac{2\eta t_r}{3kn} \left(\frac{dV}{dz}\right)^2 . \quad (6)$$

If the energy of quasi thermal motion $E = kT_e$ is sufficient, the abrasive particle slips along the surface of the workpiece and cuts its surface roughness. It is assumed that for best results one must use the abrasive particles with dimensions smaller than the magnitude of the surface roughness of the workpiece [4, 6].

In MRPF the bulk magnetic force acts on magnetic particles moving in the flow of the elements of a continuous medium [10]:

$$f_m = \nabla\left(\mu_0 \mu H^2\right) = -\nabla\varphi . \qquad (7)$$

Magnetic particles interacting with each other form aggregates with bonding energy of the pair of particles in it:

$$E_p = \mu_0 \mu J_m^2 V_m^2 < \frac{3}{2} kT_e , \qquad (8)$$

where V_m is particle volume, J_m its magnetization.

Force $\vec{f}_m$ holds the jet of MRPF pressed against the surface of the truncated spherical tool of radius R, rotating with the frequency ω. The jet flow and every its element with dimensions L_y and L_z, bounded by an inner radius R, an outer radius R_1 while the axial depth of Ox axis is $h = R_1 - R$ are rotated together with the rotor of the tool with angular velocity of ω . The centrifugal force of inertia $F_c = m\omega^2 R = \rho\omega^2 dV$ with bulk density $f_c = \rho\,\omega^2 R$ acts on line element which is directed radially the tool and opposite to the magnetic force. The full volume force is equal to the sum of magnetic and centrifugal components and could be written as:

$$\left.\begin{aligned} f &= \left| f_m + f_c \right| = -\left|\nabla(\mu_0 \mu \chi H^2)\right| + \rho_m \omega^2 R = \\ &= \rho_m \left(-\frac{\varphi(R)}{R\rho_m} + \omega^2 R \right) = \rho_m g; \\ g &= -g_m + \omega^2 R; \\ g_m &= \frac{\mu_0 \mu \chi H^2}{R\rho_m}, \end{aligned}\right\} \qquad (9)$$

where g is acceleration of MRPF, g_m is acceleration of the motion of magnetic particles under the influence of the magnetic volume force. On the abrasive particle of density ρ_a buoyancy acts:

$$f_a = (\rho_m - \rho_a)\left(\frac{\varphi(R)}{R\rho_m} + \omega^2 R \right) = \rho g_a , \qquad (10)$$

where $\rho = \rho_m - \rho_a$, $g_a = \dfrac{\varphi(R)}{R\rho_m} + \omega^2 R$ in which magnetic component is directed parallel to the centrifugal force and presses the abrasive particles to the workpiece and not to the tool. Thus, there is a redistribution of the two types of particles of complex filler of MRPF in the gap workpiece-tool associated with the extrusion of the filler particles into the upper layer of the jet to the surface of the workpiece.

Moving a MRPF element against the impact of "gravity force" from the tool surface from point R to the point located at a distance x from the center of the rotor tool or on $x - R$ from the tool, leading to the commission of work [9]:

$$U = -\int_R^x mg\,dx = -mg\left(x - R\right). \qquad (11)$$

Volume density of a number of particles on the height x at effective temperature T_e is determined by Boltzmann law:

$$nn(x) = n_0\, exp\left(-\frac{U(x)}{kT_e} \right) = n_0\, exp\left(-\frac{mg\,(x - R)}{kT_e} \right),$$

where n_0 is normalization coefficient.

The number of magnetic particles in the volume element of a layer $L_y L_z\ \ x - R$ is equal to:

$$\begin{aligned} N\ \ x &= L_y L_z \int_R^x n\ \ x\ \ dx = \\ &= L_y L_z \int_R^x n_0\, exp\left(-\frac{mg\ \ x - R}{kT_e} \right) dx. \end{aligned} \qquad (12)$$

Conversion of intergrand expression at $h = \dfrac{mgx}{kT_e}$ and $h_1 = \dfrac{mgR}{kT_e}$ and integration along the whole layer (12) results in:

$$\left.\begin{aligned} N(x) &= \frac{L_y L_z kT_e}{mg} \int_{h_1}^{h} n_0\, exp\left(h_1 - h\right) dh = \\ &= \frac{L_y L_z kT_e}{mg} n_0\, exp\left(h_1\right) \int_{h_1}^{h} exp\left(-h\right) dh; \\ N(x) &= \frac{L_y L_z kT_e}{mg} n_0 \left[1 - exp\left(h_1 - h\right)\right]. \end{aligned}\right\} \qquad (13)$$

Substitution expression for h gives:

$$N(x) = \frac{L_y L_z kT_e}{mg} n_0 \left(1 - exp\left(-\frac{mg\,(x - R)}{kT_e} \right) \right).$$

The total number of the particles in the layer $L_y L_z\ \ R_1 - R$ is equal to:

$$\begin{aligned} N &= \frac{L_y L_z kT_e}{mg} n_0 \left(1 - exp\left(h_1 - h_2\right)\right) = \\ &= \frac{L_y L_z kT_e}{mg} n_0 \left(1 - exp\left(-\frac{mg\,(R_1 - R)}{kT_e} \right) \right). \end{aligned} \qquad (14)$$

Therefore the normalization coefficient is:

$$n_0 = \frac{Nmg}{L_y L_z kT_e \left(1 - exp\left(-\dfrac{mg\,(R_1 - R)}{kT_e} \right) \right)} \qquad (15)$$

and a number of particles in the layer $L_y L_z\ \ x - R_1$, the density of the particles at the height $x - R_1$ over the tool are:

$$N\;x\;=N\frac{1-exp\left(-\frac{mg\;\;x-R}{kT_e}\right)}{1-exp\left(-\frac{mg\;\;R_1-R}{kT_e}\right)}\,; \tag{16}$$

$$n\;x\;=\frac{Nmg\left(1-exp\left(-\frac{mg\;\;x-R}{kT_e}\right)\right)}{L_yL_zkT_e\left(1-exp\left(-\frac{mg\;\;R_1-R}{kT_e}\right)\right)}\,. \tag{17}$$

The number of magnetic particles in the layer of the thickness *b*, adjunct to the detail, is equal to:

$$\left.\begin{aligned} &N\;\;R_1-b\;=L_yL_z\int_{R_1-b}^{R_1}n\;\;x\;\;dx=N\;\;x\;= \\ &=\frac{L_yL_zkT_e}{mg}n_0\left(1-exp\left(-\frac{mgb}{kT_e}\right)\right) \\ &\qquad\text{or} \\ &N\;\;R_1-b\;=N\frac{1-exp\left(-\frac{mgb}{kT_e}\right)}{1-exp\left(-\frac{mg\;\;R_1-b}{kT_e}\right)}, \end{aligned}\right\} \tag{18}$$

The number of abrasive particles in this layer is determined similarly as:

$$N_a\;\;R_1-b\;=N_a\frac{1-exp\left(-\frac{m_ag_ab}{kT_e}\right)}{1-exp\left(-\frac{m_ag_a\;\;R_1-b}{kT_e}\right)}\,, \tag{19}$$

where m_a is mass of the abrasive particle, ρ_a its density, ρ_m is density of magnetic particles, and:

$$g_a=\left(1-\frac{\rho_a}{\rho_m}\right)\;g_m+\omega^2R\;\;. \tag{20}$$

Used MRPF contains particles of magnetically sensitive material - carbonyl iron with the density $\rho_m = 7.5 \times 10^3$ kg/m^3, with an average magnetization $J_m = 5 \times 10^5$ A/m, the size of $d = 1 \times 10^{-6}$ m, with a volume concentration of $C = 0.36$. As an abrasive material nanodiamond is used of volume concentration $C_a = 0.05$, the particles of which have a density $\rho_a = 3.5 \times 10^3$ kg/m^3 and the size of $d = 5 \times 10^{-7}$ m. Spot sizes of MRPF contact with the workpiece to be polished according to [6] are chosen as $L_y = 5 \times 10^{-3}$ m, $L_z = 5 \times 10^{-3}$ m. According to the results of rheological measurements, we find that a steady flow is observed at a shear rate $\dot{\gamma} \geq 10^{-2}$ - 10^{-3} s^{-1}, i.e. approximately we choose the relaxation time $t_r = 10^{-3}$ s. Given these parameters a distribution of particles across the gap of polishing device and in the zone of contact with the workpiece of thickness *b* is calculated, as well as their dependence on shear rate. The results are shown in Figs. 5, 6.

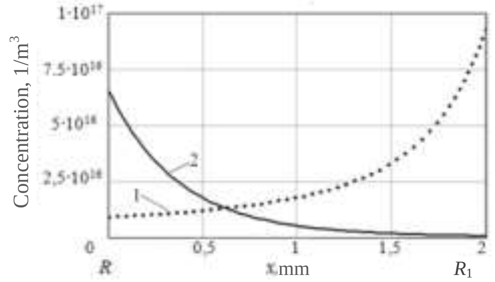

Fig. 5 Distribution of volume concentration of magnetic particles *1* and abrasive particle *2* across the gap workpiece-tool

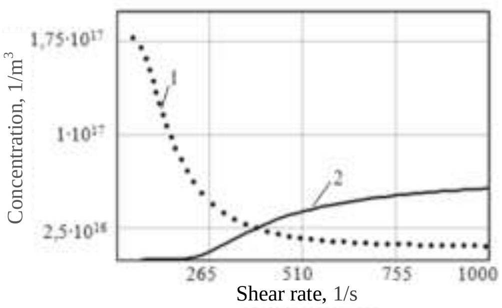

Fig. 6 Dependence of volume concentration of the magnetic particles *1* and the filler particles *2* on the shear rate in the gap workpiece-tool

If the abrasive particles are in equilibrium with the magnetic particles, then at the quasi-static process their temperatures are identical. Pressure of the mass of abrasive particles can be defined as:

$$p_a\;\;\dot{\gamma}\;=n_akT_e=n_a\frac{2\eta\;\;n_a\;\;t_r}{3}\dot{\gamma}^2\,, \tag{21}$$

where $\eta\;\;n\;=\eta_0\;\;1+an\;\;n$.

Experimental dependence of the viscosity on the concentration of particles can be represented as a superposition of linear and quadratic Einstein dependencies [10].

Full pressure of MRPF jet on the workpiece is composed of elastic magnetic pressure of the jet and of kinetic pressure and the magnetic and abrasive components. Pressure of abrasive component consists of the pressure exerted by the magnetic component and the kinetic pressure. Its value is calculated for the received data. When a steady flow - shear rate $\dot{\gamma}=200\,\text{s}^{-1}$, it is equal to 1.293 kg/ms^2.

A known pressure of abrasive component of the complex MRPF filler at a selective velocity of sliding abrasive particles $V_a = dV / dz \times d$ allows one to determine the rate of removal of material by cutting off parts of its surface roughness by sharp edges of abrasive particles, according to [6] from formula $dM / dt = kp_a\, dV / dz \times d$. It is necessary to note that, if the abrasive material which is harder than the material of the workpiece (for example, nanodiamond) contains large spherical particles, then they may uneven workpiece surface without destroying the surface.

4. Conclusion

The motion of magnetic and abrasive particles in the current magnetorheological polishing fluid between the surface of polished workpiece and polishing tool is considered as the flow of their mixtures in local equilibrium with the same effective temperatures, depending on the flow rate. It is shown that under the magnetic field due to the magnetic pressure the abrasive particles move to the workpiece surface and are pressed against her. Expression is determined for the pressure of the abrasive particles, under the influence of which during Couette shear, material removal from the workpiece surface is carried out at a speed proportional to this pressure and the gradient of the velocity of MRPF flow near the surface of the workpiece.

References

1. **Shaw, M.C.** 1996. Principles of Abrasive Processing, Clarendon Press, 574 p.
2. **Khomich, N.S.** 2006. Magneto-Abrasive Treatment of Workpieces, Minsk, BNTU, 218 p. (in Russian).
3. **Kordonsky, W.; Jacobs, S.** 1996. Magnetorheological finishing, International Journal of Modern Physics 10(23/24): 2837-2848. http://dx.doi.org/10.1142/S0217979296001288.
4. **Kordonsky, W.; Gorodkin, S.** 2011. Material removal in magnetorheological finishing of optics, Applied Optics 50(14/10): 1984.
5. **Rusetsky, A.; Novikova, Z.; Gorodkin, G.; Korobko, E.** 2011. Development of magnetostructuring fluids with controlled rheology for the finishing polishing technique of optical workpieces, Proceedings of NAS B 55(5): 97-104 (in Russian).
6. **Kordonsky, W.; Shorey, A.; Tricard, V.** 2006. Magnetorheological jet (MR jet) finishing technology, Journal of Fluids Engineering 128(21): 46-58.
7. **Loskutov, A.Y.** 2007. Dynamic chaos: systems of classic mechanics, UFN 177(9): 989-1015.
8. **Karion, A.; Hunt, M.L.** 2000. Wall stress in granular Couette flows of mono-sized particles and binary mixtures, Powder Technol. 109: 145-163. http://dx.doi.org/10.1016/S0032-5910(99)00233-8.
9. **Shillikng, G.** 1976. Statistical Physics in Examples, Moscow, MIR, 431p. (in Russian).
10. **Nigmatulin, R.I.** 1978. The Basics of Mechanics of Heterogeneous Media, Moscow, Nauka, 336p. (in Russian).

A. Mokeev, E. Korobko, A. Bubulis

DISPERSINIŲ MAGNETOREOLOGINIO SKYSČIO DALELIŲ KONCENTRACIJOS PASISKIRSTYMO TARPELYJE TARP RUOŠINIO IR POLIRAVIMO ĮRENGINIO ĮRANKIO MODELIAVIMAS

R e z i u m ė

Magnetinių ir abrazyvo dalelių judėjimas magnetoreologiniame poliravimo skystyje tarp poliruojamo ruošinio paviršiaus ir poliravimo įrankio yra nagrinėjamas kaip jų mišinio pusiausvyros tekėjimas esant tai pačiai temperatūrai, priklausantis nuo tėkmės debito. Tyrimo rezultatai parodė, kad abrazyvinės dalelės, veikiamos magnetinio lauko slėgio, juda link ruošinio paviršiaus ir yra įspaudžiamos. Yra nustatyta abrazyvinių dalelių slėgio, kuris įtakoja medžiagos pašalinimą nuo ruošinio paviršiaus dėl Couette tėkmės greičiu, proporcingu slėgiui ir magnetoreologinio poliravimo skysčio tekėjimui šalia ruošinio paviršiaus greičio gradientui.

A. Mokeev, E. Korobko, A. Bubulis

SIMULATION OF CONCENTRATION DISTRIBUTION OF DISPERSED PARTICLES OF MAGNETORHEOLOGICAL FLUID IN THE GAP WORKPIECE-TOOL OF FINISHING POLISHING DEVICE

S u m m a r y

The motion of magnetic and abrasive particles in the current magnetorheological polishing fluid between the surface of polished workpiece and polishing tool is considered as the flow of their mixtures in local equilibrium with the same effective temperatures, depending on the flow rate. It is shown that under the magnetic field due to the magnetic pressure the abrasive particles move to the workpiece surface and are pressed against her. Expression is determined for the pressure of the abrasive particles, under the influence of which during Couette shear, material removal from the workpiece surface is carried out at a speed proportional to this pressure and the gradient of the velocity of MRPF flow near the surface of the workpiece.

Keywords: polishing processes, magnetorheological fluid, abrasive, stream.

Received June 15, 2014
Accepted April 04, 2014