Journal of Engineering Physics and Thermophysics, Vol. 75, No. 2, 2002

RHEODYNAMIC PRECISION SURFACE TREATMENT CONTROLLED BY A MAGNETIC FIELD

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UDC 532.135+621.932

The basic regularities of the process of contactless precision treatment of a surface which is based on the distinctive features of the rheodynamics of a magnetized magnetorheological suspension are considered. The influence of the basic parameters of a magnetorheological suspension on the indices of the process of treatment is investigated. The high efficiency of the technology and the possibility of creating a completely automated process based on it are shown.

The progress made in submicron technologies in microelectronics and the demand for optoelectronic systems capable of operating with high-power laser emission and radiation stimulated further development of the methods of precision treatment. Even in large-scale production, one must often ensure the reproduction of the prescribed shape of a surface at a level of hundredth fractions of a light wave with a microroughness (runs) of no more than 10 Å and a defect-free surface layer.

Such indices are attained by using the processes of removal of a material which ensure rigid monitoring of the force action of the abrasive grain on the treated surface. The working tool must have time stability in geometric and abrasive parameters and ensure a safe thermal regime in the treatment zone.

Therefore, contactless methods of treatment are introduced into practice [1]. The formation of a continuously renewable tool with prescribed geometric parameters and the force action of an abrasive grain are monitored in the given case by the hydrodynamic characteristics of the flow of an abrasive phase [2], the magnetic buoyancy force [3], or the ponderomotive force [4].

The vast possibilities for automated treatment of a wide range of workpieces of glass, ceramics, semiconductors, and nonferrous metals are provided by the technology of magnetorheological polishing [5].

The possibility of treatment of workpieces with a noncolloidal suspension of magnetic and abrasive particles has been predicted in [6]. The actual implementation of the process of polishing with the use of magnetorheological suspensions in the lap regime has been described in [7]. The microroughness of the surface at a level of 100 Å was attained in the case of high efficiency of the process.

Further improvement of the technology of magnetorheological polishing is based on the distinctive features of the rheodynamics of a magnetized magnetorheological suspension.

In the general case, abrasive magnetorheological suspensions represent a noncolloidal suspension of magnetic and abrasive particles with a Newtonian dispersion medium. Differing little from a Newtonian fluid beyond the magnetic field, a magnetic rheological suspension totally changes its rheological characteristics in the field. Polarization of the particles and their subsequent dipole–dipole interaction lead to a fundamental rearrangement of the mesostructure of the fluid. Chain aggregates oriented along the field lines are formed in the dispersion medium, and the medium acquires viscoplastic properties; under such conditions, the rheological state of the magnetorheological suspension is described quite reliably by the Bingham law

$$\tau = \tau_0 (H) + \eta\dot{\gamma} .$$

The yield strength of the bulk structure of the magnetorheological suspension with the volume concentration of the dispersed phase φ = 0.2–0.3 in fields of 200–300 kA/m can attain 10^4–10^5 N/m^2.

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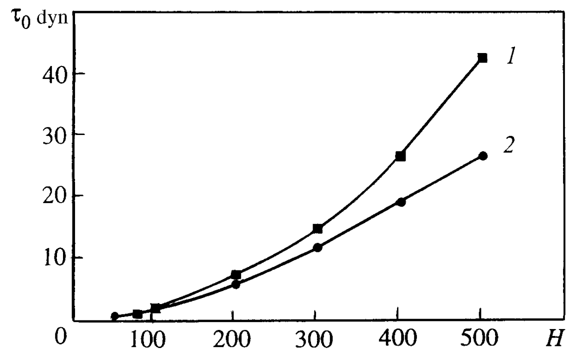

Fig. 1. Influence of the magnetic field on the dynamic yield strength of the magnetorheological suspension: 1) disk of steel; 2) disk of glass. τ_{0dyn}, kPa; H, kA/m.

The flow of viscoplastic media in slot channels with a moving wall is characterized by the occurrence of the core-flow zone (elastic zone) that can either be adjacent to one channel wall or be located inside the flow depending on the applied stresses, the rheological parameters of the medium, the geometry of the channel, and the pressure gradient [8]. At the boundary with the wall, in the case of motion of viscoplastic fluids and especially concentrated suspensions, one observes the effect of wall slip [9], which begins for certain values of the tangential stress on the wall $\tau_s < \tau_0$. It is assumed that the effective slip of the dispersion system and not the true slip occurs. The condition of adhesion of the medium to the channel walls is observed but only for the continuous phase of the system forming a thin film (over which the disperse system is sliding) near the wall and not for the entire system. For aqueous suspensions the thickness of this film can be a hundredth of a micron. For suspensions with the dislocation character of the mesostructure the film thickness turns out to be nonuniformly distributed over the channel length and the conditions on the wall combine the effects of the internal (viscous) friction and of the external (boundary) friction dependent on normal pressure [8, 9].

A similar effect is also observed in the case of flow of magnetorheological suspensions, especially concentrated ones, in strong magnetic fields. The slip effect increases if the channel walls are made of a smooth unmagnetizable material and degenerates if the channel walls represent a rough surface manufactured from a material of high magnetic permeability. In this case, the particles of the dispersed phase are attracted to a channel wall and become fixed on it owing to the inhomogeneities of the magnetic field which are induced by the roughness of the wall and the effect of magnetic mapping [10, 11].

The effect of slip of a magnetorheological suspension is illustrated by the dependences of the dynamic yield strength τ_{0dyn} (approximation of the linear portion of the curve of flow of the magnetorheological suspension to the τ axis) on the magnetic field strength H; these dependences are obtained on a disk–disk rotational viscosimeter (Fig. 1).

The difference in the character of the dependences $\tau_{0dyn} = f(H)$ presented by curves 1 and 2 is caused by the effect of wall slip, which is observed when one disk is manufactured from smoothly polished glass (curve 1). If both disks are manufactured from a material with a high value of the magnetic permeability (steel 3), the slip of the magnetorheological suspension is absent and the values of τ_{0dyn} increase by 30% (curve 2).

The distinctive features of the rheodynamics of a magnetized magnetorheological suspension during its flow in a channel with a moving wall provide the basis for realization of the process of magnetorheological polishing. The scheme of the process is given in Fig. 2a. The workpiece 1 to be treated is mounted above the rough surface 2 manufactured from an unmagnetizable material. The surface 2 carries out a translational movement with linear velocity v relative to the vertical axis. The layer of the magnetorheological suspension 3 is continuously fed to its surface via an 8×3 mm slot nozzle using a pump. The bipolar inductor of a magnetic field 4 with an interpolar distance nearly equal to the nozzle width is mounted above the surface; the inductor creates a nonuniform magnetic field with the gradient (grad $H \sim 5 \cdot 10^7$ A/m^2) directed to the moving surface. The field is nonuniform over the width of the layer of the magnetorheological suspension; it sharply decreases at the layer boundaries and at the entry-exit of the magnetorheological suspension from the channel formed by the workpiece surface and the moving surface. In the zone of feed of the magnetorheological suspension to the surface, the magnetic field strength is about 20 kA/m.

Arriving from the nozzle at the moving surface, the magnetorheological suspension, under the action of the field, acquires a yield strength sufficient for the shape of the layer to be retained in the course of its transportation to

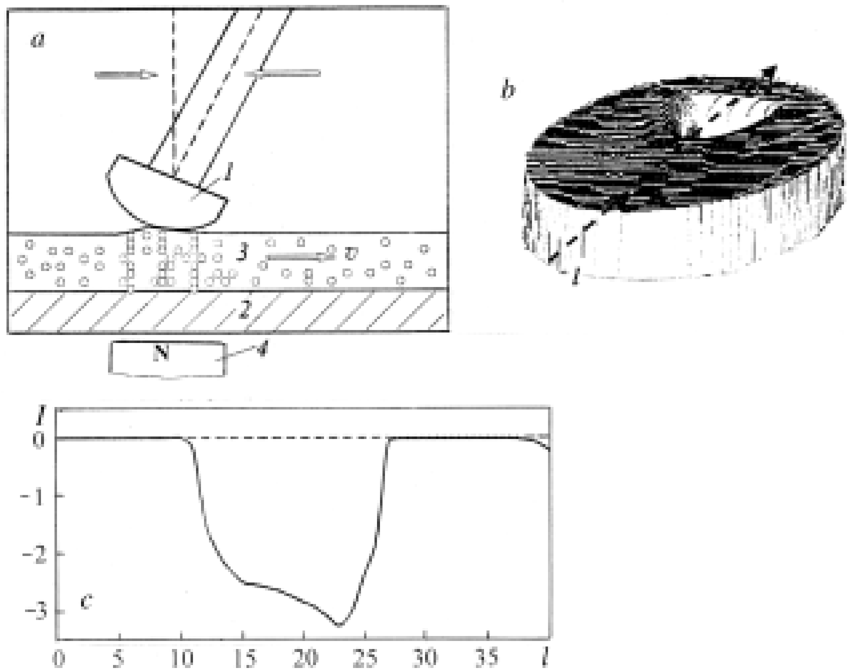

Fig. 2. Magnetorheological polishing: a) scheme of the process; b) treatment spot formed on the stationary treated surface; c) distribution of the intensity of removal of the material in the treatment spot. I, μm/min; l, mm.

the treated surface. In polishing, the workpiece to be treated is put 1–2 mm deeper into the layer of the magnetorheological suspension and the regime of flow of the magnetorheological suspension between the stationary treated and moving surfaces is realized in the working gap.

Along with the yield strength, the force acting on a nonmagnetic body (glass workpiece in this case) immersed in a magnetizable medium in a nonuniform magnetic field is the source of elasticity of the magnetorheological-suspension layer, which creates pressure on the treated surface.

The average pressure $\overline{P}_{av}$ on the spherical part of the workpiece immersed in the magnetoreological suspension can be determined from the formula

$$\overline{P}_{av} = \mu_0 M \,(H_0 - H_1)\, \frac{\alpha}{1 + \alpha}\,.$$

The shape factor α is determined by the depth of immersion h and the geometric parameters of the workpiece:

$$\alpha = \frac{h^2 R}{ab^2}\,.$$

For the typical values of the process $H_0 - H_1 \sim 100$ kA/m, $a = 3{\cdot}10^{-3}$ m, $b = 8{\cdot}10^{-3}$ m, and $h = 1.5{\cdot}10^{-3}$ m and a magnetorheological suspension with $M = 300$ kA/m, $\overline{P}_{av} \sim 4{\cdot}10^{-4}$ Pa. Such a level of working pressures cannot lead to abrasive wear of the surface and to the formation of a disrupted near-surface layer [12].

It is well known that the mechanism of polishing of glass is physicochemical and does not fit in the models of abrasive wear or thermoplastic edging [12]. Significant removal of the material can occur even at very low working pressures ($<10^2$ Pa). The particles of the dispersed phase of the abrasive suspension interact with a soft (hydrated by the aqueous dispersion medium) surface layer of glass (~100 Å) which is removed by the mechanical lapping-stimulated adsorption of molecular fragments of the glass by abrasive particles pressed to the glass surface and moving relative to the treated surface.

The dispersed phase of a magnetorheological suspension usually consists of two components: spherical particles of carbonyl iron of size 1–20 μm and abrasive particles. However, when the latter are absent the particles of car-

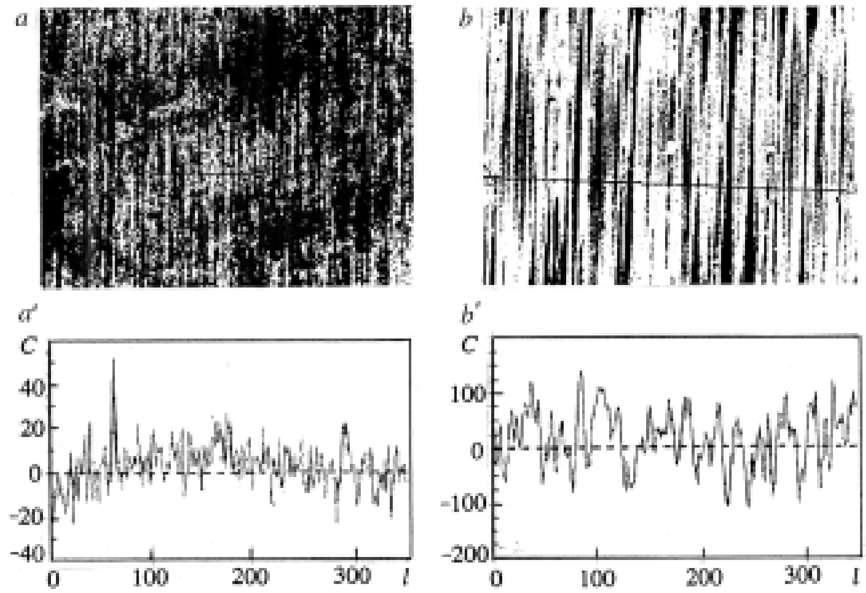

Fig. 3. Interferograms and profilograms of the surface of a stationary workpiece treated with a magnetorheological suspension with different size of the dispersed-phase particles: a and a′) particles of S-3700 carbonyl iron ($d_{av} \sim 3$ μm) and b and b′) ATW-230 carbonyl iron ($d_{av} \sim 23$ μm). C, Å; l, μm.

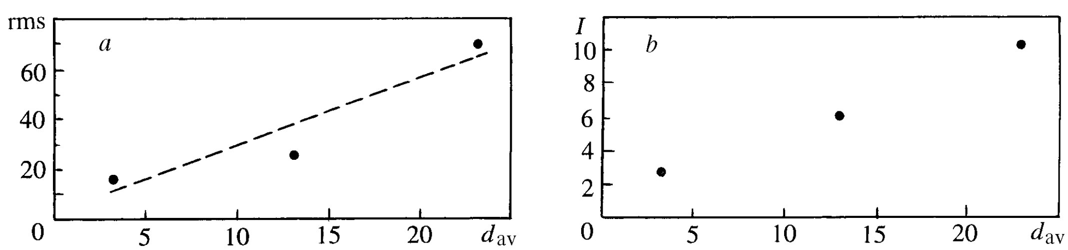

Fig. 4. Influence of the size of the dispersed-phase particles on the microroughness of the surface (a) and on the maximum intensity of removal of the material (b) in the treatment spot. rms, Å; d_{av}, μm.

bonyl iron ensure a sufficiently productive process of removal d_{av} of the material and one observes no wear of mechanically hard particles of carbonyl iron even with lengthy polishing [13].

Upon movement of the magnetorheological suspension to the zone of treatment under the action of the gradient magnetic field, the particles of the dispersed phase of the magnetorheological suspension, combined into chain aggregates, are pressed to the moving surface. One observes the outflow of gravitational water to the surface of the magnetorheological-suspension layer, i.e., to the treated surface and to the periphery of the layer over its width. As the magnetorheological suspension moves in the channel, further outflow of gravitational water occurs with increase in the compressive stresses and in the hydraulic compaction of the layer. The pore pressure partially neutralizes the normal load, which is totally transferred to the "skeleton" of the magnetorheological suspension as the suspension moves further in the working gap, and the particles of the dispersed phase make boundary contacts with the surface. Taking into account the presence of the vertical gradient of the magnetic field, we can assume the occurrence of the concentration gradient of the displaced phase over the height of the layer of the magnetorheological suspension. In the zone of contact with the rough moving surface, the concentration of the particles is nearly limiting, the particles are pressed to the surface, dislocations of the structure of the magnetorheological suspension are absent, and no slip of the magnetorheological suspension is observed.

At the surface of the treated workpiece, the concentration of the displaced phase is lower, structural dislocations are significant, and on a smooth treated surface one can expect the slip of the dispersed-phase particles which is capable of causing mechanical activation of the glass layer, hydrolyzed by the dispersion medium, and removal of the material.

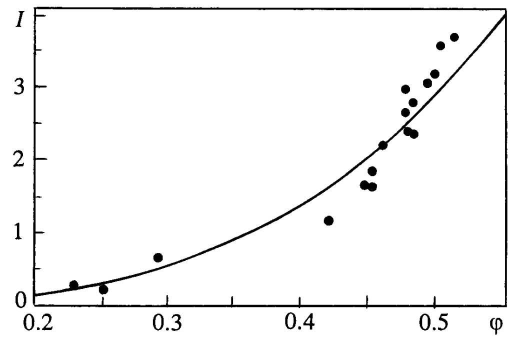

Fig. 5. Influence of the concentration of the particles of the dispersed phase on the intensity of treatment.

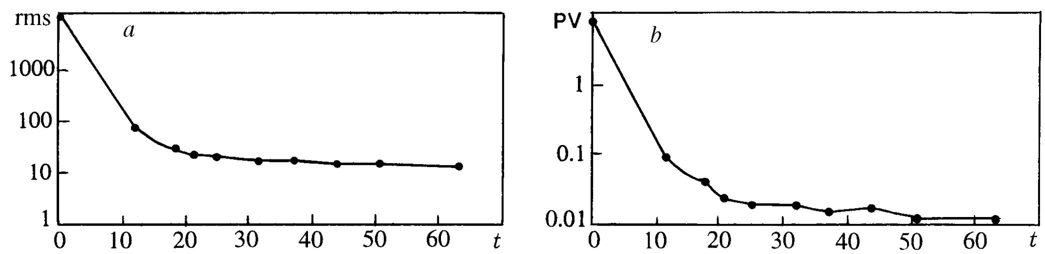

Fig. 6. Influence of the treatment time on the rms (a) and PV (b) of the treated surface. *t*, min; PV, μm.

Indeed, in the zone of contact of the magnetorheological suspension with the treated surface, one observes intense removal of the material (Fig. 2b) (treatment spot). The distribution of the intensity of removal of the material I in the treatment spot along the direction of motion of the magnetorheological suspension l is given in Fig. 2c.

The relief of the surface microstructure of glass workpieces treated in such a manner and the influence of the parameters of a magnetorheological suspension on the quality of treatment have been investigated on Zygo interferometers.

In the first stage, we studied the influence of the particle size of carbonyl iron on the surface microrelief formed in magnetorheological polishing. Lenses (rms 8 Å) of K-8 glass, thoroughly polished under the same conditions, were introduced for 0.1 sec into the layer of a magnetorheological suspension. In the experiments, use was made of three magnetorheological suspensions based on a glycerin-water mixture with the concentration of the dispersed phase $\varphi \sim 0.45$. The dispersed phase of each magnetorheological suspension represented the particles of carbonyl ion differing in average size (d_{av}); these were the particles of S-3700 ($d_{av} \sim 3$ μm), S-1000 ($d_{av} \sim 13$ μm), and ATW-230 ($d_{av} \sim 23$ μm) grades.

Figure 3 gives the interferograms (a and b) and profilograms (a′ and b′) of the surfaces of optical workpieces of K-8 glass after treatment with two magnetorheological suspensions with S-3700 (Fig. 3a) and ATW-230 (Fig. 3b) particles. It is seen that a system of parallel tracks whose depth C increases with increase in the size of the particles and whose width is comparable to their diameter is formed on the glass surface as a result of treatment. It is obvious that the microroughness of the surfaces (Fig. 4a) also increases with the particle size.

The most intense removal of the material is observed for the suspension prepared based on ATW-230 particles, and its maximum in the treatment spot is 10 μm/min (Fig. 4b). The decrease in the particle size of the dispersed phase of the magnetorheological suspension decreases somewhat the intensity of removal of the material but contributes to a substantial improvement in the quality of treatment. In the case of using the particles of S-3700 carbonyl iron ($d_{av} \sim 3$ μm), the microroughness of the treated surface is no more than 15 Å (Fig. 4a).

The influence of the volume concentration of the dispersed phase of a suspension on the intensity of removal of a material is illustrated in Fig. 5. The intensity of removal of the material for a workpiece of quartz glass increases approximately 8 times as the concentration of the dispersed phase φ changes in the range 0.25–0.5.

The given results are obtained for the case where the treated surface is stationary relative to the polishing zone. One can expect that the qualitative indices of the process become substantially improved in continuous movement of the treated surface relative to the treatment zone. It is precisely such a regime that is used to polish the entire surface. The treated surface is displaced in the horizontal plane by, for example, rotation.

In the case of treatment in the automatic regime, in accordance with the intensity of removal of the material in the treatment spot, one prescribes the regime of hunting to a spindle with a rotating workpiece mounted on it (when the workpiece is spherical relative to the axis coincident with the radius of the workpiece); the regime is prescribed according to the program calculated either by a scheme ensuring uniform removal of the material over the entire workpiece surface or by a scheme ensuring the correction of the shape of the workpiece if its initial surface differs from the prescribed one. The attained parameters of treatment are very high. One is able to decrease the microroughness of the K-8 glass lens from 8000 to 10 Å over the period of time t = 30–40 min (Fig. 6a); the deviation of the surface shape from the prescribed one (PV) is at a level of 0.01 μm (Fig. 6b).

The given results indicate the high efficiency of use of a magnetorheological suspension as an abrasive medium for creation of the technology of automated precision treatment controlled by a magnetic field.

The process is efficient in treatment of a wide range of materials (glass, nonferrous metals, semiconductors), including very hard ones (sapphire and diamond), and of surface shapes (planes, convex and concave spherical and aspherical surfaces, etc.).

NOTATION

τ, shear stress; τ_0, yield strength generated by the magnetic field; η, viscosity of the dispersion medium of the magnetorheological suspension; $\dot{\gamma}$, rate of shear; φ, volume concentration of the dispersed phase; τ_{0dyn}, dynamic yield strength; τ_s, tangential stress on the wall; H, magnetic field strength; v, velocity of movement of the layer of the magnetorheological suspension; $\overline{P}_{av}$, average pressure on the spherical part of the workpiece; H_0, magnetic field strength on the moving surface; H_1, magnetic field strength at the upper boundary of the layer of the magnetorheological suspension; M, magnetization; μ_0, magnetic permeability of vacuum; α, shape factor; h, depth of immersion; a, layer height; b, layer width; R, radius of curvature of the workpiece surface; I, intensity of removal of the material; l, running coordinate on the workpiece surface; d_{av}, average size of the particles; C, depth of the tracks; t, time; PV, deviation of the surface shape from the prescribed one. Subscript: s, shear.

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