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SOME FEATURES OF THE MAGNETORHEOLOGICAL EFFECT

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The rheological properties of magnetorheological suspensions (MRS) are investigated in a wide concentration range of particles of the disperse ferromagnetic phase in the presence of a magnetic field. It is shown that, along with an increase in the concentration of ferromagnetic particles, the range of control of the viscous stress increment in an MRS can be broadened by changing the size and shape of the ferromagnetic particles, introducing nonmagnetic particles into the dispersion medium as well as by heating the medium to the Curie temperature.

The possibility of control of the rheological and thermophysical properties of magnetorheological suspensions (MRS) within wide limits by applying a magnetic field has allowed their use for creation and upgrading of modern technologies: electrohydroautomatics, precision polishing of parts made of glass, ceramics, and semiconducting materials, of heat exchangers, etc. [1, 2].

In a magnetic field of a prescribed intensity an MRS acquires distinct viscoplastic properties, and the magnetoviscous effect achieved (an increase in the effective MRS viscosity) is determined by such factors as the magnetic properties and size and shape of particles of the disperse ferromagnetic phase, as well as their concentration.

Among the great variety of disperse ferromagnetic materials produced (powders of ferrites and magnetodielectrics), magnetorheological technologies employ powders of carbonyl iron used to create high-frequency devices in the radioengineering industry. Their doubtless merit is high values of magnetic susceptibility and saturation magnetization. The most widely used and cheap powders of carbonyl iron of the type R-10, R-20, R-100, etc., contain spherical particles sized to microns and are distinguished by polydispersivity. The range of particle size distribution lies within 0–20 μm. Here, the mean particle size differs insignificantly (from 1 to 3.5 μm) in the various powder modifications. The electromagnetic parameters of all powder modifications of carbonyl iron are practically unchanged in the range of frequency characteristics of systems with magnetorheological control. Therefore, in order to broaden the possibilities of control in magnetorheological technologies, use is made of the concentration factor.

Depending on the sphere of application and the required range of control of rheological characteristics, the concentration of the ferromagnetic filler in actual MRSs can be varied within wide limits (from 2 to 50 wt.%). To investigate the influence of the concentration of particles of the ferromagnetic disperse phase on MRS rheological properties in a magnetic field, we used suspensions based on particles of carbonyl iron of modification R-10 with a mean size of 3.5 μm. The dispersion medium of all MRSs was prepared on the basis of hydraulic oil, grade AMG-10, with stabilizing additives in form of submicronic particles added to impart sedimentation and aggregation stability to the suspension. These particles formed coagulation structures that prevented sedimentation of heavy ferromagnetic particles and were capable of thixotropic transformations.

The rheological properties of the MRS in a magnetic field were measured by a rotary magnetorheometer based on a standard rotary viscosimeter. The magnetorheometer was equipped with an inductor of a radial magnetic field which provided application of external fields with an intensity of 0–200 kA/m to a Couette flow of the

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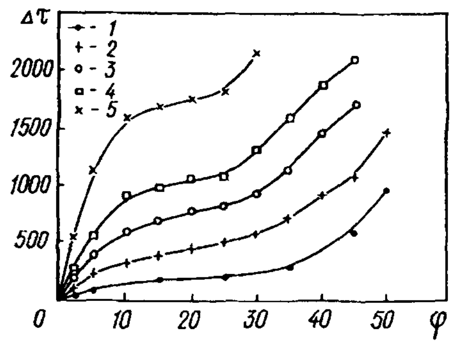


Fig. 1. Increment of viscous stresses in MRS $\Delta\tau$ versus concentration of ferromagnetic particles in magnetic fields of different intensities H: 1) $H = 20$ kA/m; 2) 30, 3) 40, 4) 50, 5) 80. φ, %; $\Delta\tau$, Pa.

investigated fluid. The entire measuring cell of the device was thermostated. The arrangement made it possible to control the investigated suspensions in the range of 0–90°C.

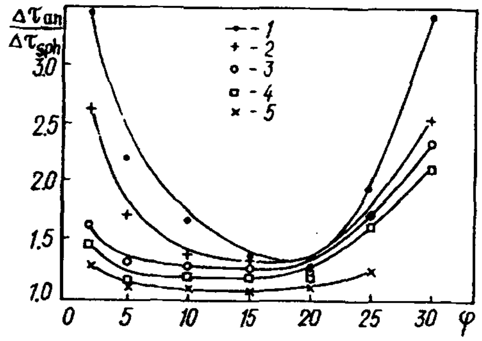
A dependence of the increment of shear stresses of the MRS on the concentration in a magnetic field $\Delta\tau = f(\varphi)$ is shown in Fig. 1 (here $\Delta\tau = \tau_m - \tau_0$, where τ_m and τ_0 are the shear stresses of the MRS at the prescribed shear rate in the magnetic field and without it, respectively.

It is found that in the range of low volumetric concentrations of particles of the dispersed ferromagnetic phase ($\varphi < 8\%$) the dependence $\Delta\tau = f(\varphi)$ is nearly linear. With an increase in the content of magnetic particles to moderate concentrations ($8\% < \varphi < 30\%$), the character of the plot changes. In this range only an insignificant increase in viscous stresses in a magnetic field is detected, which is attributed to an increase (by 5–10%) in the volumetric concentration of ferromagnetic particles. However, with a further increase in the concentration ($\varphi > 30\%$), the role of the concentration factor markedly enhances. In this case, with increasing φ the shear stresses undergo almost a quadratic increment. Such a tendency of the concentration dependence to an increase in viscous stresses is manifested for all intensities of magnetic fields (20–80 kA/m) and shear rates implemented in the experiments.

The range of control of the viscous stress increment in the MRS in the presence of a magnetic field can be considerably extended by increasing the portion of coarse particles in the composition of the polydispersed ferromagnetic powder. It is found that an increase in mean particle size of from 3 to 20 μm results in a threshold increase in the control range in magnetic fields with an intensity of up to 100 kA/m.

One more way of the improving the sensitivity of the rheological characteristics of an MRS to a magnetic field is to use a dispersed ferromagnetic phase based on anisodiametric particles. From this standpoint, particles in the form of long cylinders or elongated ellipsoids are considered to be most effective. The magnetization energy of an anisodiametric particle with its major axis collinear with the intensity vector of the magnetic field, with all other factors being equal, is much smaller than that of a spherical particle. In this respect, particles with an axis ratio of 10:1 are most effective. However, particles of corresponding size of ferromagnetics with sufficiently high magnetization are not produced. Therefore, for investigation of the influence of particle size on the rheological characteristics of the MRS the only alternative is to modify the shape of spherical particles of carbonyl iron by mechanical methods with the purpose of imparting some anisodiametric property to them. With particles of modification R-10, this was accomplished in an attritor by means of cold plastic deformation. As a result of such treatment, the particles acquired a configuration close to that of a contracted ellipsoid with an axis ratio of approximately 3:1.

Investigations of the magnetic properties of an MRS prepared on the basis of modified particles of carbonyl iron ($\varphi = 10\%$) show that the saturation magnetization corresponds to that obtained for a suspension of spherical particles of the same concentration. This indicates that for the mentioned technology of particle treatment, their internal structure changes insignificantly and, as a consequence, their electromagnetic parameters are retained. However, an analysis of the curves of static magnetization of the given MRS and one based on spherical particles shows an increase of magnetic susceptibility in low-intensity fields (0–100 kA/m). The magnetic susceptibility undergoes an almost twofold relative increase, which is attributed to the change in the shape of particles. In



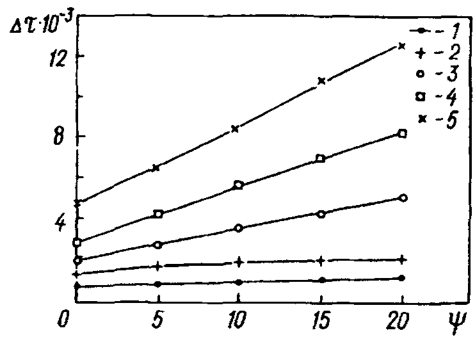


Fig. 2. Relative increment of shear stress of MRS in a magnetic field H due to changing the shape of the particles: 1-5), see Fig. 1.

Fig. 3. Maximum increment of shear stresses in MRS with $\varphi = 20\%$ versus concentration of nonmagnetic particles ψ in magnetic fields of different intensities H: 1) $H = 20$ kA/m; 2) 40, 3) 80, 4) 120, 5) 200. ψ, %.

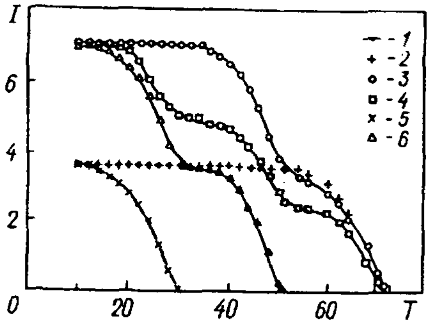
accordance with the character of magnetization, an increase in the absolute increment of shear stress in a magnetic field for a suspension based on anisodiametric particles also occurs in low-intensity fields (up to 80 kA/m). This effect is manifested more strongly for an MRS with a relatively low concentration of anisodiametric ferromagnetic particles ($\varphi < 5\%$) as well as in highly filled systems ($\varphi > 17\%$) and it increases as far as the concentration increases (Fig. 2).

The increment of viscous stresses in an MRS in a magnetic field can be increased by introducing nonmagnetic particles into the dispersion medium of the suspension. This phenomenon is interesting from a practical point of view. In carrying out magnetorheological polishing to increase the efficiency of stock removal, abrasive additives are introduced into an MRS [3]. The particles of the abrasive filler can be of different sizes (from hundredth parts to several microns) and are distinguished by an irregular form of their surface.

It is found that the introduction of nonmagnetic particles into an MRS with a prescribed concentration of the dispersed ferromagnetic phase does not change the character of the MRS magnetization curve. But at the same time an analysis of the rheological curves of flow of an MRS with abrasive additives in a magnetic field shows a considerable increase in the increment of visous stresses as compared to an MRS with the same concentration of ferromagnetic (but without nonmagnetic) particles, with all other conditions being equal. It is established that the effect increases with the intensity of the magnetic field. For instance, the introduction of nonmagnetic particles with a volumetric concentration of 20% into an MRS (use was made of electrocorundum particles with a size of 10 μm) results in a twofold increase in $\Delta\tau$ (Fig. 3). In this case, alongside the spatial structure formed by ferromagnetic particles the structural units of nonmagnetic particles develop in the MRS [4], the destruction of which is associated with additional dissipation.

In considerations of the rheological characteristics of an MRS in a magnetic field it is usually assumed that the magnetic properties of the ferromagnetic particles are independent of temperature. At the same time, ferromagnetic materials are distinguished by a fundamental property: destruction of the long-range magnetic order upon heating till its disappearance (the Curie temperature). Therefore, the combined influence of a magnetic field and temperature turns out to be a rather effective mechanism of control of the rheological characteristics of an MRS.

The Curie temperature of carbonyl iron is much higher than the working temperature range of the dispersion media traditionally used in an MRS. In order to create thermosensitive magnetorheological suspensions, use can be made of ferrite powders whose Curie temperature is considerably lower and approaches to room temperature. Ferrites possess high magnetic susceptibility in low-intensity magnetic fields and insignificant saturation magnetization. Therefore the magnetoviscous effect reached in using ferrites as the dispersed phase of an MRS is much less pronounced than for an MRS based on carbonyl iron particles. In the experiments, we used powders of magnetically soft Ni-Zn ferrites with the same magnetic properties at temperatures far from the Curie temperature. At the same time the Curie temperature of each of the three powders was different and equal to 30,



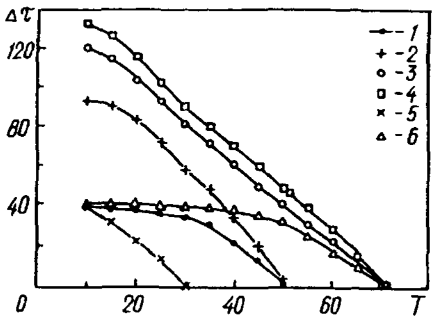


Fig. 4. Temperature dependence of magnetization of MRS with dispersed phase based on Ni-Zn ferrites: 1) $T_C = 51°C$, $\varphi = 10\%$; 2)) 71°C and 10%; 3) mixture consisting of two ferrites (T_C, $\varphi = 10\%$ + $T_C = 71$ °C, $\varphi = 10\%$); 4) mixture consisting of three ferrites ($T_C = 30°C$, $\varphi = 6.6\%$ +$T_C = 51°C$, $\varphi = 6.6\%$ +$T_C = 71°C$, $\varphi = 6.6\%$), 5) $T_C = 30°C$, $\varphi = 10\%$, 6) mixture consisting of two ferrites ($T_C = 30°$; $\varphi = 10\%$ +$T_C = 51°C$, $\varphi = 10\%$). *I*, kA/m; *T*, °C.

Fig. 5. Temperature effect on increment of viscous stresses in MRS with dispersed phase based on Ni-Zh ferrites at $\gamma = 563.2$ sec^{-1}, $H = 60$ kA/m): 1) $T_C = 51°C$, $\varphi = 10\%$; 2) mixture consisting of two ferrites ($T_C = 30°C$, $\varphi = 10\%$ +$T_C = 51°C$, $\varphi = 10\%$); 3) mixture consisting of two ferrites ($T_C = 51°C$, $\varphi = 10\%$ +$T_C = 71°C$, $\varphi = 10\%$); 4) mixture consisting of 30°C, $\varphi = 6.6\%$ +$T_C = 51°C$, $\varphi = 6.6\%$ +$T_C = 71°C$, $\varphi = 6.6\%$); 5) $T_C = 30°C$, $\varphi =$

51, and 71°C, respectively. The dispersion medium for an MRS of this type was chosen from the condition of low sensitivity of the viscosity to temperature variation.

We investigated the temperature dependence of magnetization of an MRS whose dispersed phase consisted of one, two, or three powders with different Curie temperatures T_C (Fig. 4). The magnetization curves show distinct inflection points corresponding to the Curie temperature of each of the three components. Such a variation of the magnetic properties of the MRS with temperature variation is reflected adequately on the rheological curves of MRS flow in a magnetic field. The magnetoviscous effect degenerates completely as the temperature approaches the Curie point (Fig. 5). For multicomponent MRSs containing ferrite powders with different Curie temperatures, the temperature dependence of the increment of viscous stress in a magnetic field represents a smooth curve. As the temperature increases, each of the components successively loses its magnetic properties when the temperature realized in the experiment exceeds the Curie temperature corresponding to one or other component of the composition. The temperature dependence of viscosity of such MRSs in a magnetic field is higher than that of ordinary liquids by orders of magnitude.

NOTATION

$\Delta\tau$, increment of shear stress; φ, concentration; T_C, Curie temperature; ψ, concentration of nonmagnetic particles; γ, shear rate.

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