Adhesion peculiarities at the contact of MRF with solid state in gradient magnetic field

V A Kuzmin¹, E V Korobko¹,4, V P Roizman², Z A Novikova¹, A P Dostanko³ and A O Karabko³

¹A.V. Luikov Heat and Mass Transfer Institute of NAS Belarus, 220072, 15 P. Brovka str., Minsk, Belarus
²Chmelnitski State University, 29016, Institutskaya str. 11, Khmelnytskyi, Ukraine
³Belarusian State University of Informatics and Radioelectronics, 220072, 6 P. Brovka str., Minsk, Belarus

E-mail: evkorobko@gmail.com

Abstract. The results of studying surface properties of MRF, obtained by experimental investigation of the influence of the magnetic field on adhesion indices and spreading characteristics of the finite volume (a drop) of the suspension are reported.

1. Introduction
Formation of the structure of magnetic fluids and magnetorheological suspensions from the magnetization of the elementary particles and its effect on flow patterns, despite the continuous study [1–7], is still not well understood. This is especially true of finite volumes of fluids during the spreading with the open outer boundary in the form of a layer on the surface of objects, in particular in terms of gradient magnetic fields. However, this problem is relevant when creating the technology of formation films with oriented structure. This work is undertaken to address this gap. The influence of external fields on the relaxation processes and surface free energy is investigated in relation to the more conductive metallic liquids. In fact, a number of papers are dedicated to the problem of determining the influence of the magnetic field on the spreading of metals on the surface. In [6, 7] a theoretical and experimental analysis of spreading mercury droplets on the surface of polycrystalline zinc is carried out. Several stages corresponding to different regimes of spreading that are determined in the current were discovered. The influence of various internal (surface tension, viscosity, diffusion, dissolution, chemical reaction) and external (gravitational and electric fields) factors on the metallic liquid spreading on a solid surface has been determined. In [6] it was theoretically demonstrated the possibility of the magnetic field to influence the kinetics of spreading of the metal drop. Assuming that the influence of the magnetic field can be carried out through the ponderomotive force, and taking as the driving forces of the spreading a surface tension force, a viscous friction and Lorentz force, based on the solution of the Navier-Stokes equation a continuity equation was obtained for the dependence of the spreading on the intensity of the magnetic field. Its solution gave a result that can be interpreted as an equivalent increase in the viscosity of the fluid.

There are also studies on the influence of external fields on the surface phenomena of structuring fluids – electrorheological fluids (ERF), that differ by a powerful force interaction of polarized

⁴Corresponding author.
particles of the filler [8, 9], as well as magnetic (colloidal) liquids [10, 11], that do not exhibit such significant rheological changes in magnetic fields.

Studies of these problems in relation to magnetorheological fluids are scarce and fragmented, both theoretically due to lack of closure relations to determine the force interactions of structuring particles and the surface free energy and experimentally, since most studies have been based on a detailed study of the magnetic parameters of the medium, due to peculiarities of their structure and surface phenomena, the change of which is affected by a non-stationary or non-uniform magnetic field.

It is known that in a homogeneous bulk phase there are no forces in the absence of external fields when describing it macroscopically. Points of the bulk phase are characterized only by the densities of the components present in it, the densities of the free and total energy and entropy. By microscopic description of the bulk phase the local forces (including through magnetic interactions) and molecular fields should be considered. By averaging over the volume, which includes a sufficient number of molecules and ions, they also vanish in contrast to the transition zone between the two phases in which the strength of interaction are damped further deep into each of the adjacent phases. These forces will be called surface forces. Accordingly, the density of the components that make up at least one of the phases, the densities of the free and total energy and entropy vary in a direction across the interfacial zone.

The present work is dedicated to the experimental determination of the characteristics of the magnetic field effect on the force components of the motion equation (Navier-Stokes equations), which solution together with the continuity equation will further allow to evaluate the characteristics of MRF spreading (time spreading, instantaneous values of the radius of spreading). The objectives of this paper are to establish patterns of the magnetic field influence on adhesive performance and characteristics of the spreading of the finite volume (a drop) of MRF suspension.

2. Experimental

As an investigated material a magnetorheological fluid (MRF) based on chromium dioxide powder and MOBIL oil (MRF-X) is taken where the volume content of dispersed phase ranges from 5 to 35 vol. %.

First of all, the experiments were conducted to study the magnetic properties of magnetorheological suspensions. Magnetization curves were obtained by means of measurement with two Hall sensors using the device shown in figure 1. Measurements of the magnetization is reduced to the measurement of the induction field in the sample cell 7 with a sample of MRF and in the air gap of an electromagnet consisting of a magnetic conductor 4 and coil 5, fed by the source 6. Hall sensor 9 in the sample registers the magnitude of the magnetic induction $B$ and the sensor 8 in the air gap – the value of $\mu_0 H$.

For a sufficiently long sample (ratio of sample length to width is greater than 10) the distortion field in the sample is small.

Then the expression could be written

$$B = \mu_0 (J + H)$$

and magnetization of the sample in the field:

$$J = \frac{B - \mu_0 H}{\mu_0}.$$  \hspace{1cm} (1)

Supplying the inputs 2, 3 of differential amplifier 10 by signals from two sensors we can obtain a signal on the exit 1, proportional to the magnetization of the sample $J$, and a signal from the sensor 8 to characterize the intensity of the magnetic field $H$.

When determining the magnetization it is necessary to bear in mind that a sensor 9 occupies in the suspension the layer of a thickness $h=0.7$ mm, dividing the cylindrical sample of MRF with a radius of $R=3$ mm in two parts. This layer is not filled by the suspension, that is equivalent to the appearance in it the magnetization $\sim J$. It results in that the induction of the magnetic field in the center of the layer where a sensor 9 is situated is lower than the induction in the volume of MRF by the value of
Respectively the equation (1) gives the value of the magnetization, lowered by the value \(\Delta J = \frac{Jh}{\sqrt{h^2 + 4R^2}}\). This correction is necessary to be considered when determining the real value of the magnetization. Measurement errors for the magnetic values were within 2 %.

It is found that magnetic permeability is increased with the increase of dispersed phase concentration and is decreased with the increase of the intensity of the magnetic field which is due to the saturation in strong magnetic fields. Obtained dependence \(\mu(H)\) for MRF-X with maximal concentration of the filler is present in figure 2. Chromium dioxide CrO₂ is a hard-magnetic material and has a lower magnetic susceptibility and intensity of saturation than that of the widely used powder of carbonyl iron.

Peculiarity of MRF as magnetic material is the mobility of the carriers of magnetic moment – the particles of the dispersed phase. Therefore suspensions are magnetized substantially because of the restructuring. Formation in the magnetic field of the structures, directed along field lines increase the susceptibility of MRF in this direction.

Investigations have shown that magnetization curves on the initial section are close to linear ones up to intensities of the field 30 kA/m, i.e. MRF in this area has a constant magnetic susceptibility.
More over the initial susceptibility increases practically linearly with the increase of ferromagnetic particle concentration. In the magnetic field of about 300 mT there is a saturation of MRF no matter what concentration of the dispersed phase is. It is found, that MRF susceptibility is rather sensitive to the transformation of the structure in the process of the flow. In fact, for resting MRF the value of the initial susceptibility does not depend on the field, in the shear flow it drops with the increase of the shear rate and the decrease of the intensity of the field. These changes of susceptibility are due to the changes of the size of aggregates and their orientation along the field direction, and also due to the relaxation time of the equilibrium structure and are determined by the ratio of magnetic and hydrodynamic forces.

The rheological characteristics were obtained by means of a rheometer Physica MCR 301 by Anton Paar using a measuring cell consisting of two coaxial cylinders (the diameter of the internal cylinder is 26.7 mm, of the external one is 28.9 mm, the gap between cylinders is 1.13 mm). Measurement errors for the rheological values were within 0.5 %. The rheological characteristics are shown in figure 3.

![Graphs showing rheological characteristics of MRF-X](image)

**Figure 3.** Rheological characteristics of MRF-X: (a) flow curves at the intensity of the magnetic field: 1 – 0, 2 – 80, 3 – 100, 4 – 200, 5 – 300, 6 – 400, 7 – 500 kA/m; (b) the dependence of the yield stress on the intensity of the magnetic field; (c) the dependence of the plastic viscosity on the intensity of the magnetic field.

3. Results and discussion

With the aim of determining formation conditions of a continuous compact MRF layer the influence of the inhomogeneous magnetic field on the shape of the surface, spreading characteristics and surface tension on its interface with the air is experimentally estimated on the example of a finite volume of MRF (a drop). Laboratory equipment (figure 4) has provided the measurement conditions for the wetting angle, radius and height of the MRF drop by means of video fixation of the spreading process on the base that is the inductor of the magnetic field. Also the shape and the surface of the drops were
studied by means of Axio Lab A1 microscope by Carl Zeiss. In the experiments the composition of MRF, the size and mass of MRF drop, the induction of the external magnetic field, the bending angle of the base are varied. In figure 5 we show the dependence of the induction of the magnetic field on the distance \(z\) to the surface of the base, that was changed depending on the number of nonmagnetic additional layings (glass) with the aim of regulating the value of the intensity of the magnetic field on the surface, on which the drop fell (in its different points). The investigated suspension was put into a batcher with a diameter 1.5 or 2.5 mm. A drop of the suspension fell on the surface of the base from the given height (3.2, 11 or 20.3 cm). The height of the drop downfall did not influence substantially its parameters. At a bigger diameter of the batcher (2.5 mm) the diameter of the drop was bigger by 10 – 15% than that at a smaller diameter of the batcher (1.5 mm), for which the mass of the drop was fixed and was 28 g. It is necessary to note that the influence of the magnetic field on the process of drop formation at the end of the batcher has been noticed. In the magnetic field we needed more time for a drop creation and its downfall.

Investigations of the influence of the magnetic field on the spreading and wetting of MRF were performed for two cases. In the first case a drop fell on the surface of the base in the absence of the field. Then the induction of the magnetic field has been raised up to 160 mT. The shape of the drop has been registered in two projections (side and frontal) by means of a digital camera. Pictures of the drops on the surface of the base in the absence of the magnetic field are presented in figure 6. The diameter and the height of the drop, its wetting angle was determined visually using the pictures. Observational errors were 0.2 mm in the diameter and the height, 0.5° in the wetting angle.

When the drop falls on the base in the absence of the field it has a classical shape of the drop on a lyophilic surface. By increasing the field up to 60 mT the shape of the drop is not changed substantially, and we can detect only small spreading (the increase of the diameter by 2 – 3% and the decrease of the height down to 25%).

If a drop falls on the base under the magnetic field with the intensity of 160 mT, then it had a much smaller diameter than in the absence of the field (in 1.5 times) and twice as bigger height. These observations can confirm the influence of the magnetic field on the process of drop spreading in terms of stopping this spreading.

An interesting peculiarity is the presence of peculiar fractures on the surface of the drop closer to its peak. It is explained by the distribution of the intensity of the magnetic field in its volume and on the surface in accordance to the force lines of the magnet-base.
Figure 6. MRF drop on the surface of the base: (a) in the absence of the magnetic field, (b) under the influence of the magnetic field of 160 mT and (c) after switching off the magnetic field; side view (left), top view (right).

When decreasing the induction of the magnetic field from maximal value down to zero, the drop gets the same classical shape, as when the drop is registered in the absence of the field with a small difference in the size (the diameter of the drop without the field is 8.4 mm, the height 1 mm; when switching off the field the diameter of the drop is 7.5 mm, the height 1.1 mm). The dependence of the diameter and the height of the drop on the induction of the magnetic field is shown in figure 7.

The wetting angle of MRF $\theta$ grows with the increase of the intensity of the field (figure 8). On horizontal base the wetting angle linearly increases with the increase of the concentration of the dispersed phase. The bending of the base by $45^\circ$ leads to some deformation of the drop by the gravitation force and therefore to the change of the frontal wetting angle to the side of its increase. The dependence of $\theta$ on the concentration of dispersed phase resumes from being linear.

It was found that the magnetic field leads to the decrease of the spreading rate and the setting time for reaching the stationary parameters of the drop (figure 9) of the investigated compositions. The main spreading process has been finished in all cases in time frame of 10 s. A further dwell up to 1 minute did not result in any substantial change of the spreading radius and height. However, by longer dwelling times, especially for a high concentration suspension we have observed a huge change of the shape of the whole surface of the drop – the formation of the bump in the center and the change of the wetting angle at the interface of three phases.

After analyzing experimental results, we have studied the dependence of the radius of spreading on time until the equilibrium values are reached $R = R_0 + kt^n$, where for each MRF composition the coefficients $R_0$, $k$, $n$ depend on the intensity of the magnetic field.

It is known that in the surface layer fluid molecules have an additional potential energy in comparison with the molecules in the fluid volume. A surface layer on the whole has additional energy that is a part of the inner energy of the fluid. Coefficient of surface tension $\sigma$ represents another
additional free energy which a surface unit of the surface layer possesses. \( \sigma \) also has the meaning of the surface tension force, that is applied to a unit of length of the contour.

![Figure 7](image)

**Figure 7.** The dependence of the diameter (a) and the height (b) of MRF drop on the time of spreading in the magnetic field: (a) 1 – 160 kA/m, 2 – 0, 3 – 20, 4 – 40, 5 – 80, 6 – 120 and (b) 1 – 20 kA/m, 2 – 0, 3 – 40, 4 – 80, 5 – 120, 6 – 160.

![Figure 8](image)

**Figure 8.** The dependence of the wetting angle of MRF on the induction of the magnetic field: 1 – \( \theta \) for the diameter, 2 – \( \theta \) for the height.

![Figure 9](image)

**Figure 9.** Dependence of setting time for reaching the stationary parameters of the drop when spreading: 1 – setting time for the diameter, 2 – setting time for the height.

The surface tension was determined by means of tearing a thin plate from the surface of MRF at the condition of full wetting of its butt end in the magnetic field. In this case when tearing the film of the fluid is raised in which the gravitation force is equal to the applied force. The film of the fluid is broken and the plate starts to come off. The critical value of the force is fixed, and the surface tension is determined, that is connected to its value by means of calibration coefficient. It was stated that in maximal magnetic field the coefficient of the surface tension \( \sigma = 0.0544 \text{ N/m}^2 \), that is only by 0.0011 N/m² more than without the influence of the field.

The interaction of the inner structure of MRF with the base (adhesion characteristics) was also evaluated by the measurement of the normal tearing forces of a glass part from the base with MRF under the magnetic field. A scheme of the base and the corresponding distribution of the magnetic field are shown in figure 10(a), and the dependence of the specific tearing force on the intensity of the field in figure 10(b).
4. Conclusions

On the basis of the obtained results it can be concluded that when spreading MRF on the solid surface in the magnetic field, in addition to common considered forces, Lorentz force also appears because of the gradient magnetic field is impacting the system, which leads to the apparent increase of viscosity and the force.

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