MRF in a plate-plate magnetorheometer: Numerical insight into the particle-wall interface

H G Lagger¹, C Bierwisch and M Moseler
MikroTribologie Centrum µTC,
Fraunhofer Institute for Mechanics of Materials IWM,
Woehlerstrasse 11, 79108 Freiburg, Germany
E-mail: hanna.lagger@iwm.fraunhofer.de

Abstract. Particle-based simulations are a suitable tool to gain insight into the microstructural behavior of a magnetorheological fluid (MRF). For the application of MRF in clutches, the amount of torque transmission is a matter of particular interest. Concerning the contact between iron particles and clutch walls, several questions arise: Is a higher wall roughness beneficial for torque transmission? What is the influence of wall magnetism on torque transmission? What are the mechanisms on particle scale that lead to increased torque transmission? Inspired by a previous experimental study, we performed three-dimensional simulations based on the Discrete-Element-Method (DEM) with different wall roughnesses and different magnetic conditions to investigate the mechanisms of shear stress transmission at particle level. The simulations show that a higher wall roughness leads to higher torque transmission only in the case of non-magnetic walls. For ferromagnetic walls, no influence of wall roughness on torque transmission is observed. This is in qualitative agreement with the experimental results.

1. Introduction
Magnetorheological fluids consist of micron-sized iron particles suspended in a carrier oil. Upon application of an external magnetic field, chains of iron particles are formed along the magnetic field lines. Due to these particle chains, the MRF changes from a liquid-like to a near solid-like state. This adaptive behaviour makes MRF interesting for several industrial applications, such as dampers, clutches or actuators.

For the application in clutches, it is important to have a high amount of torque transmission. In this study, particle-based simulations were performed to gain insight into the mechanisms inside the clutch. With an understanding of the mechanisms on particle level, useful hints for the design of magnetorheological clutches with regard to high torque transmission can be derived.

Experimental studies by Laun et al. [1] on a plate-plate magnetorheometer (see Figure 1 A) show a significant effect of plate material (non-magnetic vs. ferromagnetic) and plate roughness on the measured shear stress and, thus, on the torque transmission. Different plate roughnesses were obtained by grooved plates with a defined groove geometry on the one hand (see Figure 1 B) and flat plates without grooves on the other hand. In the case of non-magnetic plates, an increase

¹ To whom any correspondence should be addressed.
of plate roughness results in a considerable increase of shear stress. For ferromagnetic plates, no influence of roughness on shear stress could be found.

Figure 1. Schematic drawing of a magnetorheometer (A) and groove geometry (B) as used by Laun et al. [1].

These effects were explained by the differences of the flux density distribution in the MRF. In the case of non-magnetic plates, the flux density reaches a maximum inside the grooves. The iron particles always move to areas of higher magnetisation. Thus, the iron particles adhere magnetically to the grooves and act as an anchor for the particle chains. This leads to an increase in torque transmission with increasing groove size. In the case of ferromagnetic plates, the flux density inside the grooves is minimal. Therefore, no iron particles will be found inside the grooves in this case.

In this work, the role of varied disc roughness for magnetic and non-magnetic material is investigated numerically. The particle-based approach allows detailed insight into the dynamics of the iron particles. Anchor effects, if existing, can be observed directly.

2. The Discrete-Element-Model

The numerical description of the MRF is based on the Discrete-Element-Method, originally proposed by Cundall and Strack [2]. In this method, the forces on each particle are computed in each time step. Afterwards, Newton’s equation of motion is integrated explicitly. Thereby, the positions of all particles are obtained for the following time step.

The forces acting on the particles are magnetic interactions, the hydrodynamic force of the fluid on the particles and a repulsive force, which describes collisions between particles and between particles and walls.

2.1. Magnetic interaction

The MRF particles are modelled as magnetic dipoles. The force between two dipoles $i$ and $j$ depends on the respective magnetic moments $\mathbf{m}_i$ and $\mathbf{m}_j$. The magnetic moments are calculated by the "mutual dipole model" as described in Keaveny et al. [3], i.e., for the calculation of the local magnetic field at a particle’s position not only the external magnetic field is taken into account, but also the contribution of every other magnetic particle. The magnetisation $\mathbf{M}$ of a particle, which is defined as the magnetic moment per particle volume, is described by the following magnetisation curve [4]

$$M = |\mathbf{M}| = M_S \tanh \left( \frac{\chi M_S H_{in}}{|\mathbf{M}|} \right)$$

where $\chi$ is the dimensionless magnetic susceptibility of the material, $M_S$ is the saturation magnetisation (in A/m) of the particles and $H_{in}$ is the absolute value of the magnetic field (in A/m) inside the particle. For our simulations, we chose $\chi = 5.25$ and $\mu_0 M_S = 2.1 \, T$. $\mu_0 = 4\pi \cdot 10^{-7} \, \frac{T \cdot m}{A}$ is the permeability of free space.
The force on dipole $i$ caused by dipole $j$ is given by

$$F_{ij}^{\text{mag}} = \frac{3\mu_0}{4\pi} \left[ \frac{(m_i \cdot m_j) r_{ij}}{r_{ij}^5} + \frac{(m_j \cdot r_{ij}) m_i + (m_i \cdot r_{ij}) m_j}{r_{ij}^5} - 5 \frac{(m_i \cdot r_{ij}) (m_j \cdot r_{ij}) r_{ij}}{r_{ij}^7} \right].$$  \hspace{1cm} (2)

Here, $r_{ij} = r_i - r_j$ is the vector connecting the centers of particle $i$ and $j$ and $r_{ij} = |r_{ij}|$ is its norm.

In the case of inhomogeneous external magnetic fields, there are additional forces on the particles due to gradients in the external magnetic field. The force on particle $i$ due to flux density $B_i$ at the position of particle $i$ is given by

$$F_{i}^{\text{mag}} = \nabla \left( m_i \cdot B_i \right),$$

where $\nabla$ is the spatial gradient. Thus, the total magnetic force on particle $i$ reads

$$F_{i}^{\text{mag}} = \sum_{j \neq i} F_{ij}^{\text{mag}} + \nabla \left( m_i \cdot B_i^{\text{ext}} \right),$$  \hspace{1cm} (3)

where $B_i^{\text{ext}} = \mu_0 H_i^{\text{ext}}$ and $H_i^{\text{ext}}$ is the externally applied magnetic field at the position of particle $i$. The required inhomogeneous magnetic fields were computed with the Finite-Element-Method and were imported into the DEM simulations.

### 2.2. Hydrodynamic interaction

The hydrodynamic interactions are modelled as a Stokes drag force of the carrier fluid on the magnetic particles,

$$F_{i}^{\text{Stokes}} = 6 \pi \eta R_i \left( v_{\text{fluid}} - v_i \right),$$  \hspace{1cm} (4)

where $v_i$ is the velocity of particle $i$, $R_i$ is the particle radius, $v_{\text{fluid}}$ is the velocity of the carrier oil at the particle’s position and $\eta$ its viscosity. The simulations were performed with a shear rate of 1000/s. The oil viscosity was chosen as $\eta = 5$ mPa s. The fluid velocity in the case of flat walls can be described as a linear Couette flow. For the simulations with rough walls, the required transient velocity fields were computed with the Finite-Element-Method and were imported into the DEM simulations.

### 2.3. Numerical rheometer

The three-dimensional model of a plate-plate magnetorheometer consists of two parallel walls confining the MRF in vertical direction. In the two horizontal directions, periodic boundary conditions are applied. The MRF particles are modelled as magnetic spheres. Each wall is modelled as an ensemble of overlapping, non-magnetic spheres (see Fig. 2).

All spheres have a diameter of 5.0 $\mu$m. The simulations were performed with 33 % volume fraction of particles in the suspension. To investigate the influence of wall roughness and magnetic flux density distribution, simulations with different wall profiles and with varying flux density profiles were performed.
Variation of wall profiles:

- Walls without grooves (flat walls).
- Walls with small grooves. Wall profile as in Figure 1 B, with \( dy = 6 \mu m \) and \( dz = 16 \mu m \).
- Walls with large grooves. Wall profile as in Figure 1 B, with \( dy = 12 \mu m \) and \( dz = 32 \mu m \).

Variation of flux density profiles:

- Homogeneous flux density
- For grooved walls:
  - Flux density \textit{minima} in the grooves (as in the case of ferromagnetic discs)
  - Flux density \textit{maxima} in the grooves (as in the case of non-magnetic discs)
- For flat walls: Alternating flux density minima and maxima along the wall.

3. Results

3.1. Anchor effect

Visualisations of the simulations confirm that the particles move to the locations of highest flux density, as predicted by theory. The particle-based nature of the simulations allows to determine whether or not an anchor effect is present in the shear cell. We define that \textit{no} anchor effect is present, if slip does occur directly at the interface between the walls of the shear cell and the nearby layer of MRF particles. On the other hand, we define that an anchor effect is present, if the region where slip occurs is at least one particle diameter away from the wall, not including the grooves.

In Figure 3, snapshots from simulations with homogeneous flux density are shown. The particles are coloured according to the initial horizontal position (Figure 3 A). If an anchor effect is present, the particle layers below the upper wall and above the lower wall should have the same colour as the adjacent wall, since the position relative to the wall did not change. In the case of homogeneous magnetic field, no anchor effect can be observed considering the differing colours of the wall and adjacent particles.

Snapshots from simulations with inhomogeneous flux density distribution are shown in Figure 4. In the case of flux density maxima in the grooves, MRF particles are pinned to the wall inside the grooves and act as an anchor to the other particles. In the case of flux density minima in the grooves, the particles are anchored at the flux density maxima outside the grooves. Thus, there is no slip at the particle-wall interface in both cases. Additionally, we simulated a case where the walls are flat, but where an inhomogeneous flux density profile is present nonetheless, with alternating minima and maxima along the wall. Also in that case,
an anchor effect is observed, indicating that the presence of grooves is not necessary for the manifestation of an anchor effect.

The results are summarised in Table 1.

Table 1. The presence of an anchor effect in the simulations. Yes: Anchor effect was observed in the simulation. No: Anchor effect was not observed.

|                        | Homogeneous flux density | Inhomogeneous flux density |
|------------------------|--------------------------|----------------------------|
|                        | Minima in the grooves    | Maxima in the grooves      |
| No grooves             | No                       | Yes                        |
| Small grooves          | No                       | Yes                        |
| Large grooves          | No                       | Yes                        |

Figure 3. Snapshots from simulations with homogeneous flux density. A) Walls with small grooves, initial configuration. B) Flat walls, snapshot after 1.5 ms. C) Walls with small grooves, snapshot after 1.0 ms. D) Walls with large grooves, snapshot after 1.5 ms. Colouring according to initial horizontal position.

Figure 4. Snapshots from simulations with inhomogeneous flux density. A) Walls with small grooves; flux density maxima inside the grooves; anchor effect inside the grooves. B) Walls with small grooves; flux density minima inside the grooves; anchor effect outside the grooves. C) Flat walls; alternating flux density maxima and minima along the wall; anchor effect at regions of flux density maxima. Snapshots were taken after 1.5 ms simulation time. Colouring according to initial horizontal position.
3.2. Shear stress

The calculation of shear stress in the simulation is based on the Kirkwood stress tensor [5,6]. The results are shown in Table 2.

Table 2. Shear stress in the simulation in kPa. Values are averaged from two independent runs.

|                         | Homogeneous flux density | Inhomogeneous flux density |
|-------------------------|--------------------------|---------------------------|
|                         | Minima in the grooves    | Maxima in the grooves     |
| No grooves              | 2.04                     | 3.80                      |
| Small grooves           | 3.97                     | 4.01                      |
| Large grooves           | 4.13                     | 3.94                      |
| Relative stress change from small to large grooves | 4.0 % | -1.7 % | 17.8 % |

The shear stress is lowest in the case of no flux density gradient and no grooves. The change from small to large grooves only results in a significant shear stress increase in the case of flux density maxima in the grooves.

4. Discussion

4.1. Comparison with experimental results

The anchor effect was proposed by Laun et al. [1] to account for differences in the measured shear stress in the MRF shear cell.

In the simulations, the anchor effect can be observed both for flux density minima and for flux density maxima inside the grooves. Even in the case of flat walls an anchor effect can be produced by a suitable magnetic flux density profile. This demonstrates that the attractive magnetic force of the wall is sufficient to pin particles to the wall, irrespective of the wall profile. In the case of homogeneous flux density, no anchor effect can be observed.

In the case of flux density maxima inside the grooves, large grooves show an increase of the shear stress by 17.8% compared to small grooves. This effect is not observable for a flux density profile with minima inside the grooves. These findings qualitatively are in agreement with the experimental findings of Laun et al. [1]. They observed that in the case of non-magnetic walls, corresponding to flux density maxima inside the grooves, a higher wall roughness leads to higher shear stress transmission. In the case of ferromagnetic walls where flux density is minimal inside the grooves, no such increase of shear stress was measured. This was explained by the presence of anchor effects in the former and by the absence of anchor effects in the latter case.

From the simulations, no correlation between anchor effect and shear stress can be deduced, since an anchor effect is present in all cases of inhomogeneous flux density distribution. Furthermore, in the simulations with homogeneous flux density, there is a significant increase of shear stress from flat walls to walls with small grooves. In both cases however, no anchor effect occurs. Switching from small grooves and homogeneous flux density to small grooves with flux density minima inside the grooves, no significant difference in shear stress is measured, although anchor effects occur in one case and not in the other. Thus, according to the present results, the anchor effect - as it was defined in this paper - seems to be neither sufficient nor necessary for an increase of shear stress in the simulations.

It remains to say that Laun et al. might have had a different definition of anchor effect in mind, e.g. only considering anchoring inside the grooves. In that case the explanations of the effects by Laun et al. are not contradictory to the simulation results presented here.
4.2. Predictive power of the model

The presented model reproduces correctly several aspects of magnetic particle dynamics: movement of the particles in direction of the flux density gradient, chain formation along the magnetic field lines, and shearing and breaking of the chains due to wall and fluid movement can be observed in the simulations. The scope of validity of the model can be limited due to the following aspects:

- Finite-Size-Effects: Due to the high computational effort, the simulations were performed with smaller systems than the experiments in Laun et al. [1]
- The fluid phase was treated as a background velocity field. There is force coupling from the fluid on the particles, but not vice-versa.
- The magnetic particles are modelled as magnetic dipoles. To treat the near field interaction more accurately, also higher multipoles could be taken into account (see Ref. [3]).

It remains to be investigated if the results presented here can be generalised to bigger systems and to what extent the mentioned approximations influence the simulation results.

5. Conclusions

In this work, we presented a model to simulate magnetorheological fluids at the particle-level based on the Discrete-Element-Method. The principal characteristics of magnetic particle dynamics can be observed in the simulations.

The shear stress in the simulations was analysed and discussed with respect to the presence of anchor effects. In the simulations with inhomogeneous magnetic fields, the MRF particles are pinned to the walls at the locations of maximum flux density. This so-called anchor effect can be observed in all cases: When the flux density maximum is located inside the grooves, but also when it is located between the grooves, and when there are no grooves at all. The magnetic field gradient alone is sufficient to keep particles pinned at the wall, independent of the geometrical details. In the simulations with homogeneous magnetic field, no anchor effect was found.

The analysis of shear stress shows, that for flux density maxima inside the grooves, an increase of wall roughness results in an increase of shear stress. Similar results were found in experiments with non-magnetic wall material, which corresponds to flux density maxima inside the grooves. For flux density minima inside the grooves, no significant difference in shear stress could be observed in experiments or simulations with varied wall roughness. Based on the observations of this study, these findings cannot be explained by the presence or absence of anchor effects, since anchor effects and high shear stresses were not found to be systematically related.

6. Acknowledgements

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7. References

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