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Research articles

Magnetic field angle dependent hysteresis of a magnetorheological suspension

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ABSTRACT

Magnetorheological (MR) materials are of growing interest for a development and realisation of adaptive components and damping devices. The influence of the magnetic field orientation on the rheological properties of smart materials like MR fluids or magnetic hybrid composites is a key aspect which still is not fully understood, but occurs in almost every real life MR application. To cope with the practical needs and efficiently utilise these smart materials while taking into account their material phenomena experimentally validated practice-oriented models are needed. The authors use a coupled phenomenological approach to adjust and discuss a developed theoretical model based on experimentally obtained data. In addition the data helps to get a better understanding of internal processes and interrelations in MR suspensions.

1. Introduction

Suspensions of magnetic soft microparticles are usually referred to as magnetorheological (MR) fluids, suspensions of single domain nanoparticles as ferrofluids. If particles are suspended in a cross-linked elastomeric matrix instead of a fluid the resulting compound is called MR elastomer. An externally applied magnetic field provides remote control of the magnetic materials' physical properties, wherefore these materials are widely used in numerous technical applications. For a multitude of applications with MR materials there is no precisely defined, homogeneous magnetic field. Heading for an efficient utilisation of MR materials sophisticated material models capable of describing the dependency of rheological properties on field strength, temperature, load type and field angle are needed. The influence of the field angle is the only environmental parameter of the latter mentioned still being unsatisfactory described.

For the measurement of field angle dependency of ferrofluids a couple of theoretical and experimental approaches were realised and discussed for example by [1–5]. As ferrofluids show only a weak formation of superstructures the main reason for these investigations is the determination of the influence of field orientation on vorticity of the nanoparticles ([6]). In contrast to FF the behaviour of MR fluids is significantly affected by the formation of e.g. rod-like or net-like superstructures in presence of an external magnetic field, were the orientation of these superstructures changes with the magnetic field orientation [7].

Despite the multitude of different scientific works for ferrofluids just very few works focus on the influence of magnetic field orientation on the behaviour of MR fluids [8,9,7]. Most scientific works consider a parallel (angle between field direction and loading direction $\alpha = 0^\circ$) or a perpendicular field orientation ($\alpha = 90^\circ$). Experimental works by KUZHIR et al. [9] are performed for arbitrary but discrete field directions using a pressure driven flow in a planar or circular capillary. This experimental setup enables investigations on the magnetic field direction relative to the direction of flow. KUZHIR et al. utilise tailored helical capillary tubes that need to be manufactured for every discrete inclination angle. An arbitrary variation in the field angle or an investigation of highly viscous or elastomer samples therefore is not possible, reducing transferability. Additionally the field orientation at the inlet and outlet of the capillaries could overlay the results for a specific angle. More scientific attention is given to the different modes of MR fluid operation, i.e. shear, valve and squeeze modes [10].

Regarding the characterisation of MR elastomers depending on magnetic field orientation in [11–15] new measuring devices utilising permanent magnets were presented. Both experimental setups have several limitations due to positioning inaccuracies

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between different measurements (because of the necessary repositioning of samples) and differing normal forces. Moreover the setup shown in [11] allows only a change of the field angle in 90° steps.

The established way to analyse most MR materials is under rotational shear using rotational rheometers or for MR fluids additionally under squeeze flow using capillary rheometers (Fig. 1a,b). For commercial rotational rheometers just one field direction parallel to the centre of rotation can be analysed. With special rotational rheometers the field lines can also be directed radially, yet not being able to look at other field angles [4], [6, figure 3.10]. With a capillary rheometer the field direction can be changed as done by KUZHIR et al. but it is impossible to test highly viscous fluids or MR elastomers and it is not possible to measure shear stresses directly. A measurement principle known for rubbers but rarely used for MR fluids is a translatory device, better known as WILLIAMS- or GOODRICH-plastometer [16,17], where shear is applied by translating two parallel plates to each other (Fig. 1c). The advantage of translatory rheometers over the other mentioned types is the possibility to test a broad range of materials from fluid to solid and to measure resulting shear stresses directly while being able to change field orientation. For the field orientation dependent anisotropic characterisation of a broad range of MR materials a specialised translatory rheometer – the Magnetic Field Angle Testing Device (MFATD) – was recently introduced in [18], which is used in this work.

For an unambiguous definition of the direction of the magnetic field strength $\vec{H}$ it is necessary to define two field angles α and β as illustrated in Fig. 2a. At a first glance we focus solely on shear testing a MR fluid for different field angles α, where the shear plane is positioned as shown in Fig. 2b. For this scenario under the influence of a magnetic field the model expectation would be a formation of particle superstructures and their perfect alignment in the direction of field (Fig. 2c). Most rheological models neglect any form of slipping. This could be slip between the specimen and the shear plates as well as slip inside the specimen close to the shear plates. For both cases measurement data would show a behaviour not solely representing the test specimens material behaviour but a combined behaviour of the test material and frictional effects. The herein strived approach provides a possibility to incorporate frictional effects in further considerations, focussing on a practical applicability. In particular, being able to quantify frictional effects would be an opportunity to substantiate wall slip problems.

This study is organized as follows. First, basic properties of the used MR fluid are given and the novel Magnetic Field Angle Testing Device (MFATD) is briefly introduced. Results of experiments at different magnetic field angles are presented subsequently and obtained data are discussed from the phenomenological point of view. Finally, conclusions and outlook are given.

2. Experimental

2.1. MR fluid

The commercially available MR fluid 'MRF-140CG' provided by Lord Corporation was used in our study. Using vibrating sample magnetometry the magnetisation curve of the fluid sample shown in Fig. 3 is obtained. The MR fluid has about 38 Vol.–% of magnetic microparticles with a mean size of approx. 5 μm. The viscosity of the carrier liquid of the MR fluid is 0,012 Pa s. Utilising a conventional rotational rheometer MCR 502s by AntonPaar with an MRD magnetic cell and a plate-plate measuring geometry dynamic flow curves (Fig. 4) and an amplitude sweep (Fig. 5) were performed.

2.2. Experimental setup

To get a deeper insight on the behaviour of MR suspensions a specialised translatory rheometer, the Magnetic Field Angle Testing Device (MFATD) was used. The MFATD was recently introduced in [18] as a promising device for a field angle dependent characterisation of a broad range of MR materials. The device has a symmetric layout with four coupled shear gaps. The symmetry minimises tilting moments due to the inevitable off-axis application of forces. Four electromagnetic coils on two separate yokes generate a mag-

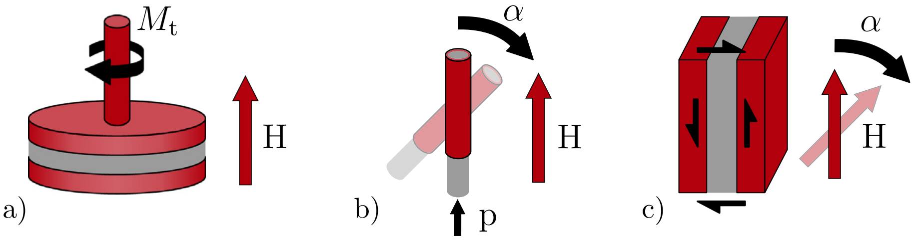

Fig. 1. Functional principle of different measurement principles for the analysis of MR materials: a) rotational, b) capillary, c) translatoric rheometer; possible angles α between the loading direction and the direction of the magnetic field strength H are shown.

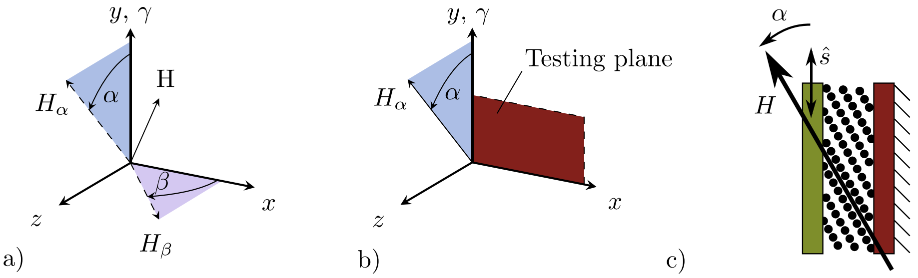

Fig. 2. a) Definition of the field angles α and β; b) testing plane position, direction of shear deformation γ and the applied field angle α, c) schematic model of particle superstructure formation inside an MRF.