Magnetic field-dependent reversal effect of the electromagnet-induced normal stress of magnetorheological materials

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Abstract

Magnetorheological (MR) materials constitute a class of magnetoactive smart materials whose physical and mechanical properties can be reversibly modulated through the application of an external magnetic field. Typically, MR materials are fabricated by dispersing magnetic microparticles within a non-magnetic matrix. This work investigates the normal stress induced in MR materials by an electromagnet (or equivalently, a non-uniform magnetic field). The results demonstrate that the stress does not vary monotonically with increasing magnetic field strength. A field-dependent reversal phenomenon in the stress variation is observed. This reversal effect is attributed to the increasing ratio of interparticle repulsion between parallel-oriented magnetic particles to the particle-electromagnet attraction as the magnetic field intensity increases.

Full Text

Preamble

Magnetic Field-Dependent Reversal Effect of the Electromagnet-Induced Normal Stress of Magnetorheological Materials

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Abstract

Magnetorheological (MR) materials are a class of magnetoactive smart materials whose physical or mechanical properties can be altered by applying a magnetic field. Typically, MR materials are prepared by mixing magnetic particles into non-magnetic matrices. In this work, we investigate the electromagnet-induced (or non-uniform magnetic field-induced) normal stress of MR materials and find that the stress does not vary monotonically with increasing applied magnetic field. Rather, a field-dependent reversal effect exists in the stress variation. This reversal effect is thought to result from the increasing ratio of interparticle repulsion between parallel magnetic particles to particle-electromagnet attraction as the magnetic field intensifies.

Keywords: Magnetorheological material; Magnetorheological finishing; Electromagnet; Normal stress; Reversal effect.

1. Introduction

Magnetorheological (MR) materials are magnetoactive particle-reinforced composites whose physical or mechanical properties can be altered by applying a magnetic field. These materials are typically prepared by mixing magnetic particles into non-magnetic matrices. Based on the mechanical state of the matrices, which ranges from fluid-like to solid-like under normal conditions, MR materials are classified into MR fluids [1-3], MR gels [4-7], MR plastomers [8-10], MR elastomers [11-14], and others. The magnetostrictive effect, magnetic field-induced deformation, and magnetic field-induced normal stress of MR materials have attracted significant attention for technical applications [15-35], particularly in MR finishing and MR materials-based sensing.

Previous studies have reported contradictory results regarding magnetic field-induced deformation [36]. For example, Ginder et al. [16] and Guan et al. [17] reported that magnetically cured MR elastomers exhibit field-induced stretching along the field direction when exposed to a magnetic field. In contrast, other studies [37-39] found that magnetically cured MR elastomers exhibit magnetic field-induced shrinking along the field direction. The magnetic field strengths investigated in these works vary considerably, ranging from dozens of mT to hundreds of mT. It is believed that the magnetostrictive effect of MR materials depends strongly on the filling state (i.e., random or structured) of magnetic particles [40-42]. Notably, a full-field deformation of MR elastomer induced by an electromagnet was measured using digital holographic interferometry [36], revealing that discretely dispersed particles lead to shrinking while grouped particles lead to stretching. Moreover, magnetic field-induced deformation depends on interparticle interactions among magnetic particles, whose magnitude varies with particle position as well as the direction and strength of the applied magnetic field [41]. The magnetic field-induced normal stress of MR materials can reflect the particle-aggregated microstructure and the potential for field-induced deformation.

For MR materials, especially flowable MR fluids, gels, and plastomers, the positions of magnetic particles influence the magnitude of interparticle magnetic interactions when a magnetic field is applied. In turn, these magnetic field-dependent interparticle interactions alter particle positions. In other words, particle positions and interparticle magnetic interactions are both field-dependent and coupled with each other, meaning that different magnetic field strengths can induce different microstructures formed by magnetic particles, resulting in field-dependent normal stress. In most MR finishing applications, electromagnets are commonly used and MR materials always work under non-uniform magnetic fields. The magnetic field-induced normal stress of MR materials is crucial in MR finishing [21]; however, the electromagnet-induced normal stress of MR materials has been seldom studied, as most research focuses on uniform magnetic field-induced normal stress. Furthermore, the magnetic field strengths investigated vary between studies and typically change over narrow ranges or at discrete magnitudes. Few works have examined the electromagnet-induced normal stress of MR materials across a continuous range of 0–1 T.

In this study, to investigate the effect of continuously changing magnetic fields on the electromagnet-induced normal stress of MR materials, we prepared MR plastomer and MR fluid samples and experimentally studied the electromagnet-induced normal stress using rheometer testing. Our results demonstrate the existence of a reversal effect in electromagnet-induced normal stress with increasing magnetic field.

2. Materials and Experiment

MR materials are typically composed of magnetic particles, non-magnetic matrices, and additives. In this work, we used carbonyl iron powder (type CIP-CN with an average diameter of 6 m and chemical composition (wt%): >99.5% Fe, <0.03% C, <0.01% N, and <0.25% O, produced by BASF SE, Germany) as the magnetic particles for preparing both MR plastomer and MR fluid samples. For the MR plastomer samples, plastic polyurethane was used as the non-magnetic matrix using the preparation method described in our previous work [8], yielding samples with 70.0 wt% carbonyl iron powder (or 24.2 vol%). For the MR fluid samples, silicone oil (type H201 with a viscosity of 20 mPa • s, provided by Sinopharm Chemical Reagent Co., Ltd, China) was used as the carrier fluid, and samples with 45.0 wt% carbonyl iron powder (or 10.0 vol%) were prepared. The magnetic field-dependent normal stress was measured using a commercial rheometer (Physica MCR 301, produced by Anton Paar, Austria). In these tests, the material sample was placed between an electromagnet base and a fixed rotor connected to a force sensor, with no magnetically permeable cover applied. A simplified sketch of the normal-stress-testing system is shown in the inset of Figure 1 [Figure 1: see original paper].

3. Results and Discussion

Figure 1 shows the electromagnet-induced normal stress of MR plastomer as the magnetic field intensity is gradually and linearly increased. The lower portion of the figure illustrates the magnetic field being applied linearly to the MR plastomer sample from an initial 0 mT to a final 930 mT over a duration of 300 s. Correspondingly, the upper portion shows the variation of electromagnet-induced normal stress during the same 300 s period. The red line represents the stress variation of a sufficiently relaxed MR plastomer sample with an initial stress of nearly 0 kPa, while the black line represents that of an insufficiently relaxed sample with an initial stress of nearly 0.25 kPa. During the initial field enhancement to 240 mT (i.e., in the first 75 s), the normal stress gradually decreases from its initial value, with a decrement of approximately 0.5 kPa for both samples. However, the normal stress subsequently reverses and increases, eventually reaching about 4.0 kPa when the field intensity reaches 930 mT (at 300 s). This decrement of 0.5 kPa is considerable relative to the final value of 4.0 kPa, demonstrating the existence of a magnetic field-dependent reversal effect in the field-induced normal stress of MR plastomer samples. The reversal point is approximately the same for both samples, and the initially residual stress counteracts the enhancement of the magnetic field-induced stress.

Figure 2 [Figure 2: see original paper] shows the effect of a suddenly applied magnetic field on the normal stress of MR plastomer. The lower portion of Figure 2 illustrates the magnetic field application process: the field is suddenly applied at 15 s, maintained for 300 s, and removed at 315 s, with applied field intensities ranging from 120 mT to 930 mT. When the field intensity is lower than 244 mT, the normal stress gradually decreases during field application, with decrements of 1.48 kPa and 0.43 kPa for fields of 120 mT and 182 mT, respectively. At a field intensity of 244 mT, the stress changes little upon field application and maintenance. For field intensities stronger than 244 mT, the stress exhibits a sudden increase from its initial value when the field is suddenly applied, with stronger fields producing stronger normal stress. The stress continues to increase during field maintenance, approaching a saturated value. When the field is removed at 315 s, the normal stress changes suddenly, approaching its initial value. These results again demonstrate a magnetic field-dependent reversal effect of electromagnet-induced normal stress for field intensities ranging from 120 mT to 930 mT, with a reversal point at 244 mT.

We further investigated the electromagnet-induced normal stress of MR fluid, as shown in Figure 3 [Figure 3: see original paper], which compares stress variation under suddenly applied and gradually, linearly enhanced magnetic fields. The lower portion of Figure 3 shows the field application processes: the rectangular red line indicates a 726 mT field suddenly applied at 20 s, maintained for 300 s, and removed at 320 s; the wedged blue line indicates a field applied at 20 s with initial intensity of 0 mT and gradually, linearly enhanced to 726 mT over the next 300 s, then removed at 320 s. In the upper portion, the square-marked red lines and triangle-marked blue lines show the corresponding normal stress variations. For the gradually applied field, the normal stress decreases gradually to approximately -0.43 kPa at 250 s (when the field intensity reaches 557 mT), but then quickly reverses and increases over the next 70 seconds as the field enhances from 557 mT to 726 mT. In contrast, for the suddenly applied field, the normal stress exhibits a sudden increase and changes little during field maintenance, although an unexpected sudden drop occurs. In a successive repeat test (shown as the relatively upper lines), the reversal point differs from the former test and the stress is slightly stronger during field application, although the final field-induced normal stress is approximately equal.

The reversal effect in electromagnet-induced normal stress of MR materials arises because the magnetic field is non-uniform and the affected space changes as the field intensifies. When the magnetic field is relatively weak, magnetic particles in MR materials are attracted to the electromagnet, causing the normal stress to decrease. In this regime, the attracting force between magnetic particles and the electromagnet is stronger than the interparticle repulsion between parallel magnetic particles. As the field becomes stronger, the interparticle repulsion can exceed the attracting effect, causing magnetic particles to form needle-like microstructures (similar to a hedgehog erecting its needles when attacked), which results in the normal stress being reversely enhanced.

4. Conclusions

In this work, we experimentally studied the electromagnet-induced normal stress of MR materials, including MR plastomer and MR fluid. We found that the variation of normal stress is not monotonic with increasing applied magnetic field. Initially, as the field intensifies, the normal stress gradually decreases from its initial value, with this decrement being considerable. When the field is enhanced to a certain extent (e.g., 240 mT for MR plastomer and 557 mT for MR fluid in this study), the normal stress reverses and increases. This magnetic field-dependent reversal effect of field-induced normal stress in MR material samples results from the varying ratio of interparticle repulsion between parallel magnetic particles to particle-electromagnet attraction as the applied magnetic field intensifies. When the field is relatively weak, this ratio is small, leading to a decrease in normal stress. When the field is enhanced sufficiently, the ratio increases and leads to an increase in normal stress.

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