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Experimental Study on Microstructure of Magnetorheological Fluids

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ABSTRACT: Firstly, the rheological mechanism of the magnetorheological fluid is explained in theory, secondly by using self-made magnetorheological fluid samples, the formation and evolution process ofmagneto-rheological fluidunder the action of the static magnetic field and shearing are investigatedrespectively by an ordinary microscope.Under the static magnetic field, the influence of the magnetic induction intensity on the microstructure of the magnetorheological fluid is mainly analyzed; Under the action of shearing, the evolution of the microstructure of magnetorheological fluids is studied.The research results have an important significance for optimizing the configuration of magnetorheological fluidsand design of some high performance magneto-rheological fluid-based devices.

Keyword: *magnetorheological fluid; rheological mechanism; microstructure; evolution process*

1. INTRODUCTION

Since the discovery ofmagnetorheological fluids (MR fluids) by American inventor JacobRabinow[1] in the 1940s, theMRtechnology has foundmany control-based applicationssuch as dampers, shock absorbers, brakes and clutches in automotive, aerospace andsome other industries. A structure based on MR fluids might be the next generation indesign for products where power density, accuracy and dynamic performance are thekey features[2].

A MR fluid is a type of smart fluid.Itcan be quickly converted to Newtonian fluid properties as having a higher shear yield stress and hysteresis sticky plastic body in a very short period of time, its rheological properties has significant and rapid changes with the magnitude and frequency of the applied magnetic field.Specific performances: In the absence of an applied magnetic field conditions, the MR fluidsshowed good rheological properties ofNewtonian fluid, similar to toothpaste, as shown in Figure 1(a) ; andunder the action of an external magnetic field, MR fluid is rapidly transformed into a highly viscous and plastic Bingham fluid by agood liquidity Newtonian fluid, the shape of the MR fluids along the magnetic field direction is similar to scale-like, as shown in Figure 1 (b).The phenomenon that the viscosity of the MR fluid changes with the applied magnetic field is continuous and reversible,that is, When the magnetic field is removed, theoriginal condition of the fluid is re-established, this phenomenon is called theMR effect[3].

（a）B=0 Gs（b）B=250 Gs

Fig. 1. Influences of magnetic field strength on the state of MRF

From a microscopic point of view, when there is a magnetic field around the MR fluid, the presence of magnetic particles in the fluid will be in the form of chain,which causesMR fluidviscosity increased, reduced liquidity and showed obvious properties of solids, with instant from a liquid to a solid state properties.

Experimental and theoretical studies have been reported to better understand andpredict the behavior of MR fluids. Particularly from the design prospective it is importantto establish the quantitative relationship between the rheological properties (viscosity,yield stress etc) and the volume concentration fraction of the particles and theirmagnetic properties as well as the intensity of the applied magnetic field.

Skjeltorp[4]observed the microstructureof MR fluids between two glass plates, found thatMR fluids arranged in a chainunder the effect of magnetic field.Bossiset al.[5] observed optical transmission condition withclassic thin MR fluids sealed in the two glass plates by using optical microscope and the change of its microstructure was studied by image analysis technique. Found that when the magnetic field intensity is lower, the light intensity is lower, butitis basically a constant, that there is still not formed microstructure; when the magnetic field strength at a certain value, light intensity increased rapidly, has completed the formation of microstructure.Furst and Gast[6] observed the characteristics of dipole chain and the variation of defects in the chain during the chain deformationbyusingoptical capture technology, the particles chain with cross type defects in the tensile process, defects of four particle in order to be pulled into the particle chain, and finally the formation of a complete particle chain.The results provides in-depth understanding of MR fluids microstructural changes.

Nishiyamaet al. [7] observed the arrangement of particles with different shapes under the action of magnetic field,and found that the needle like particles are not easy to form achain.Zhou et al.[8-9] found that, for the MR fluidssample with high volume fraction of particles, a kind of complicated three-dimensional structure composed of iron particles and oil may be formed under the action of magnetic field. It isalso found that there are plenty of defects, such as cracks, exist in the structure, and the defects will expand with the increasing of intensity of magnetic field.

Wang et al. [10]investigated the three-dimensionaldistribution of ferromagnetism micro-particles in MR fluids with an applied magnetic field based on the digital holography system. The transformation process of microstructure of MR fluids under an applied magnetic field is monitored in real-time, the chaining structure,chaining speed,particle sizesand responding time ofMR effect are obtained, and the responding time ofMR fluids to be millisecond level is verified.

The macroscopic properties of MR fluids depend on the morphology and the changes of its microstructure. By observing the microstructure and the process of its chain, the mechanical mechanism of the MR fluids can be revealed more profoundly.

In this paper, the formation and evolution process of MR fluids under the action of the static magnetic field and the shear are investigatedrespectively by an ordinary microscope.Under the static magnetic field, the influence of the magnetic induction intensity on the microstructure of the MR fluids is mainly analyzed; Under the action of shearing, the evolution of the microstructure of MR fluids is studied.

2. THEORETIC STUDY OF CHAIN-FORMATION MECHANISM FOR MR FLUIDS

2.1 Chain-formation mechanism

Particles in the magnetic field into chain or chain beam reasons exist many hypothesis and it representative of magnetic domain theory [1], the phase transition theory [11] and field induced dipole theory [6], However, these theories are qualitatively describe the effect of MR fluid and lacking of detailed and quantitative analysis of the chain forming process of particles. Through the numerical simulation method can well simulate the chain forming process of particles, the random distribution of the initial state of the particles gradually transformed into ordered chain structure can be reproduced, getting the conclusion that is consistent with the experimental observations [12,13], but these simulations just confirmed the fact that particles can be into chains, lacking of quantitative analysis of the mechanical mechanism of the chain.

Liet al. [14]studied the chain-formation mechanism based on the dipole theory. It is concluded that the particlesare assembled to form chains by the attracted component of magnetic force，while these chains can't be assembleddue to the repulsive component of magnetic force. The total inter-particle energy，including magnetic energyand repelling energy，are calculated in the simulation，which shows that the inter-particle energy decreased graduallyuntil the microstructure is steady.

2.2 Particle-based models of MR fluid

The shear stress of MR fluidis the most critical parameter, due mainly to the external magneticfield and the geometrical deformation of the fluid.Theoretical modelsare veryimportant in understanding the rheological and tribological behaviorsof MR fluid.However, finding such models is difficult due to thecomplexity of their mutual functional dependencies. In previousresearch[15] ,the internal energy density and shear stress in MR fluidwere derived from the magnetic interaction energy of magnetizedparticles. When two particles are separated by an arbitrary distance r,the magnetic interaction energy of a single particle$E_p$can becalculated using

$$E_P = \frac{|J_P \times V_P|^2(1-3cos^2\theta)}{8\pi\mu_r\mu_0|r|^3} \quad (1)$$

where J_P,μ_r ,μ_0 ,$r$andθare the magnetization density measured by aSQUID magnetometer, the relative permeability of water, thepermeability of a vacuum, the relative position vector, and the anglebetween the magnetic field and the relative position vectors,respectively. This equation indicates that the magnetic interactionenergy is a function of the inter-particle distance, permeability, and theangle between the position and magnetic field vectors.

The ideal distance between two chains was estimated using the sizeand volume fraction of particles for the case when the chain-likestructures are formed under a uniform magnetic field. Figure 2shows a schematic of the chain-like structure.

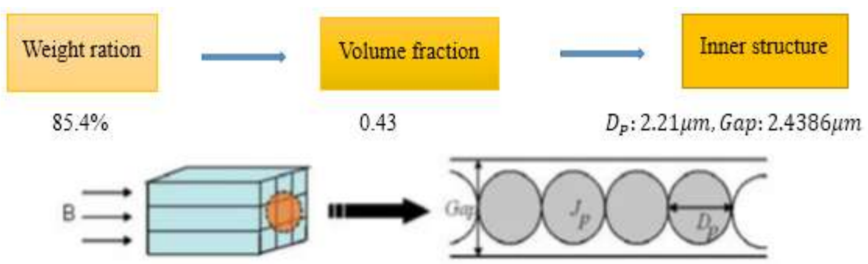


Fig. 2. Schematic of the chain-like structure of MR fluid

3. EXPERIMENTAL OBSERVATION

3.1 Static experimental observation

The static observation device of MR fluid is shown in Figure 3. Two-dimensional observations of MR fluids were carried out by ordinary microscope, respectively,obtained two-dimensional microstructure of MR fluids in the absence of magnetic field andtwo-dimensional distribution of magnetic flux structure under the magnetic field. The experimental equipment and parameters mainly include:

(1): Metallographic microscope (10XB-PC);

(2): Magnification factor M=500;

(3): Magnet (magnetic field intensity: 240GS);

(4): Slides and coverslips;

(5): High resolution digital imaging device (YH-3001, resolution: 2048×1536 effective pixels and the pixeldot size:3.2μm × 3.2μm, frame ratein max width: 8fps);

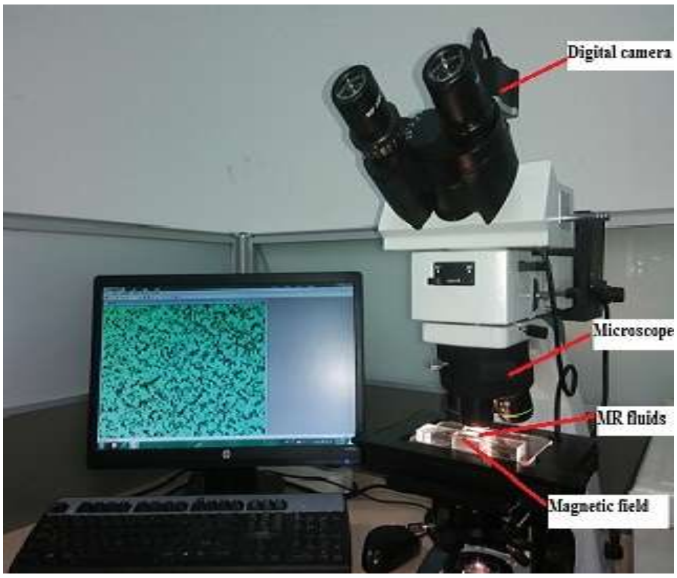


Fig. 3. Static experimental setup

First, adjusting the distance between the microscope objective and the observation samples, so that the focus falls on the sample plane; Secondly, putting the same volume fraction of MR fluidsbetween slide and coverslip; at last, shooting thestatic random distributionpictures of MR fluidsin the absence of magnetic field, as shown in figure 4.

Fig. 4.Microscopy picture of the microstructure in the absence ofmagnetic field

Applying a magnetic field on the MR fluids, continuous shooting many pictures of the magnetic flux linkage structure in magnetic field, as shown in figure 5. Selecting five continuous shooting images through microscope observation of MR fluids micro-structure test, each image selected the same flux, the chaining velocity and response time of MR fluids can also be obtained by calculating the pixel points of flux linkage.

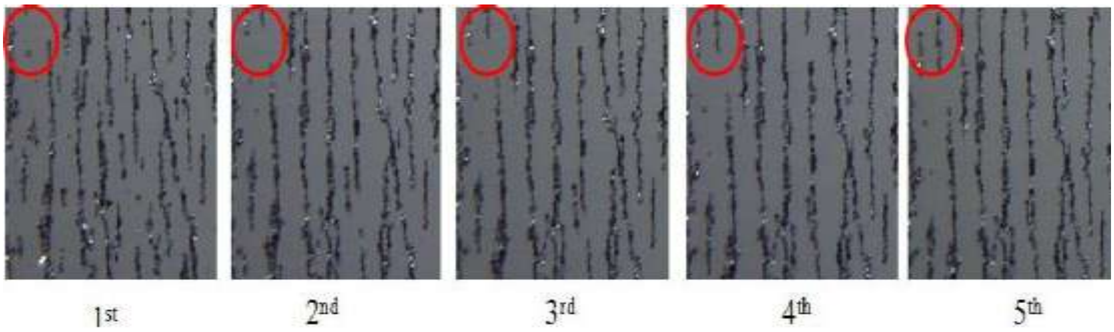


Fig. 5.The MR fluids distributionof chain structure in magnetic field

3.2Shearing experimental observation

Shearing evolution of MR fluids microstructure observation device as shown in Figure 6. In order to make good transparency of the substrate, it is made of transparent organic glass, the channel length 50mm, width 1.2mm, depth 5mm of MR fluids are placed on the observation plate. In order to eliminate the MR fluid wall effect, the gap on both sides of the two parallel plate, selection of electrical iron materials. A permanent magnet is arranged on the outer side of the two block piece, during the experiment, the MR fluid is placed near the center of the permanent magnet, so that the external magnetic field can be as uniform as possible. The role of the servo motor is to drive the lateral movement of the block, so that the flux linkage occurs shearing deformation.

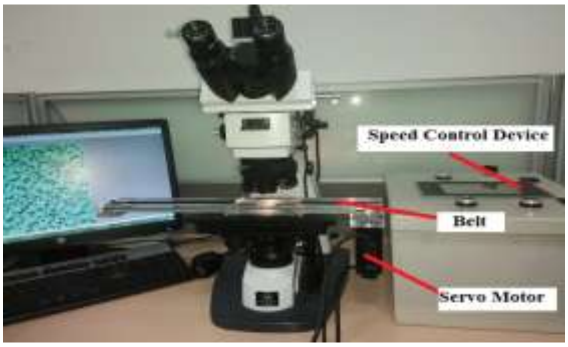
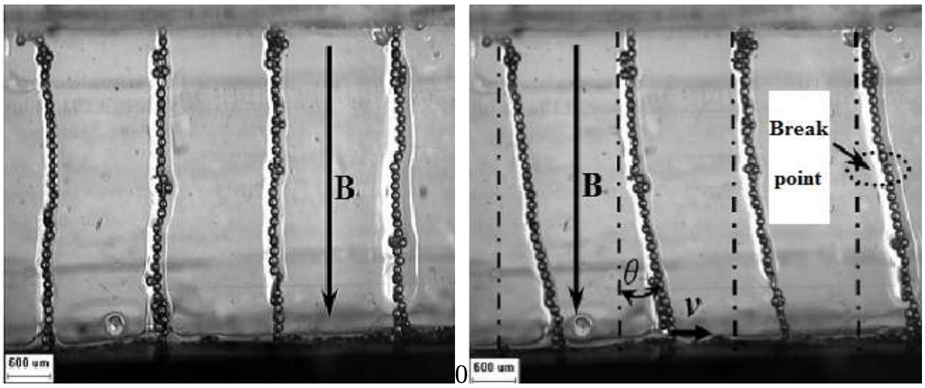
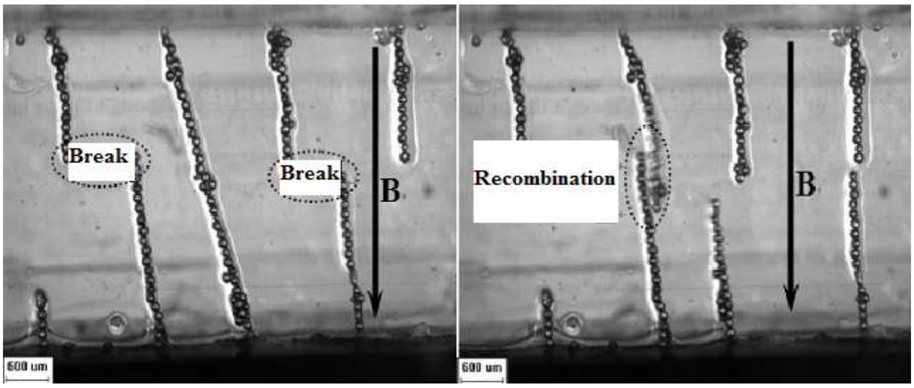


Fig. 6. Experimental setup for shearing

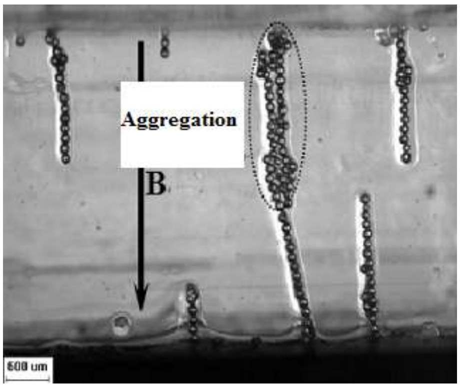
During the shearing process, the evolution of the microstructure of MR fluid is shown in Figure 7,



1.　　（b）



(c)（d）



（e）

Fig. 7.Evolution of microstructure in MR fluid during overall shear deformation

It can be seen that the microstructure evolution process of MR fluid shearing deformation process is divided into the following four steps: chaining, stretching and inclination, tensile breaking and recombination. It can be assumed that the shearing process of MR fluid is the formation of chain, stretching, breaking, recombination and stretching...... So the cycle. When the process reaches the dynamic equilibrium, the ability of the MR fluid to resist the macroscopic shear force is also stable.

2. CONCLUSION

Based on the experimental observation, the process of the formation of the MR fluids in the gradient magnetic field is studied. The results can be seen from the experiments,thatstrong changes are only achievable if shear rate is low, and it has been seen that effects like yield stress or normal stress differences are small compared to other viscoelastic fluids even at low shear rate.

Magnetic particles close and orderly arranged together, along the direction of the magnetic lines forming a distinctive chain structure. But not all of the chain is composed of particles that end-to-end, the aggregated form of particles is not only the entired chain between the two parallel plates, but also the branched chain and the isolated chain or particle clusters which are free from the carrier fluid.

On one side or both sides of the chain, some particles are attached to the chain, thereby forming a chain of defects. The existence of defects will affect the magnetic field distribution and mechanical properties of the chain.

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