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Microscopic study on the rheological properties of MRE under multi-field coupling

Tiger Hu Sun*, Qi Zhou, Xuyang Zhang, Yichen Li
(Faculty of Civil Engineering and Mechanics, Jiangsu University, Zhenjiang, Jiangsu, China)
**Corresponding author: Tiger Hu Sun,_*

ABSTRACT

Material technology has a profound impact on human civilization. Material has always been one of the three pillars of social civilization and national economy, and it is also the material basis and technical guide for the development of science and technology. As a unique intelligent material, magnetorheological (MR) material has a very important influence on the development of intelligent materials. As one of the magnetorheological materials, the magnetorheological elastomer (MRE) is popular because of their good performance and easy preparation. Since the last century, MRE has been concerned at home and abroad. With the continuous progress of the times, the research of MRE is also changing with each passing day, but for the multi-field coupling state, there is still room for the development of the influence of the micro magnetic particles of MRE on the rheological properties of MRE. Based on the knowledge of electromagnetics, this work focuses on the formation of magnetic chain in the micro state and the magnetic field around the particles and the magnetic chain. The influence of the magnetic field state of the micro magnetic particles on the rheological properties ofMRE was studied.

Keywords Magnetorheological Elastomer (MRE),Microstructure, rheological properties, multi-field coupling.

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I. INTRODUCTION

Magnetorheological (MR) material, as a popular type of intelligent material, has played an important role in promoting the development of society and economy[1-5]. It has long been widely studied by scholars at home and abroad, and its unique rheological properties make it play a crucial role in many fields[6-9].

The concept of magnetorheological fluid was first proposed by Rabinow in 1948[10]. Early magnetorheologicalelastomer (MRE) was suspensions formed by dispersing magnetic polarized particles of micron size into carrier, and it was found that the rheological properties of the material underwent drastic changes under external magnetic fields. In the 1950s, the development of MRE was once restricted due to the problems of suspension and corrosion that existed in them. Until the 1990s, with the development of technology, the preparation technology of MRE was greatly improved, making the research of this material possible again.

II. EXPERIMENTAL MICROSTRUCTURE ANALYSIS OF MRE

The MRE is a suspension composed of small soft magnetic particles with high permeability and low hysteresis mixed with the carrier liquid. It shows the characteristics of low viscosity Newtonian elastomer without external magnetic field. Under the action of a strong magnetic field, Bingham elastomer exhibits high viscosity and low fluidity as shown in Fig.1[11].

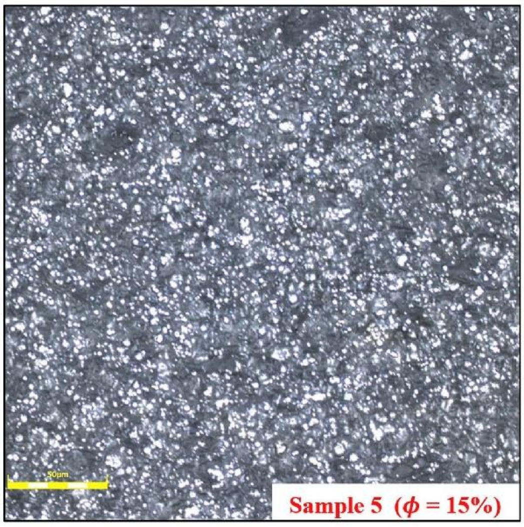

Fig.1 No external magnetic field

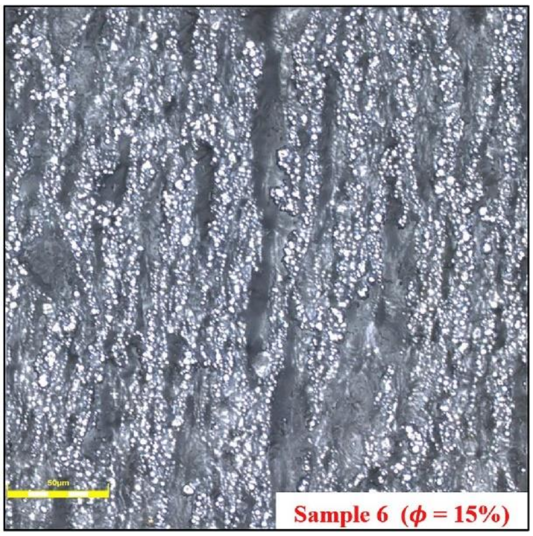

Fig.2 State of external magnetic field

The MRE exhibits unique rheological properties, mainly due to the magnetorheological effect. When there is no external magnetic field acting on MRE, its normal softer state has a lower apparent viscosity, When under the action of an external magnetic field, the magnetic particles inside are magnetized by the external magnetic field, and these magnetic particles attract each other to form a chain like microstructure. This chain like microstructure seriously hinders the fluid quality characteristics of MRE, causing the viscosity to continuously increase. This process takes a very short time and can be completed in milliseconds; As the external magnetic field increases, the mutual attraction between these magnetic particles also increases, hindering the flow characteristics becoming stronger, and even exhibiting yield stress during external deformation, i.e. exhibiting a type of solid constitutive behavioras shown in Fig.2.

III. CONSTITUTIVE BEHAVIOR UNDER MULTI FIELD COUPLING OFMRE

The Bingham model was the first macroscopic analysis model proposed by early people for MRE, and its expression is as follows[12]

$$\tau = \tau_m(H) + \eta_B \dot{\gamma} \quad (1)$$

In the equation, H represents the magnetic field strength, τ represents the macroscopic shear force, $\tau_m(H)$ represents the yield shear stress generated by the material under the action of the magnetic field, η_B represents the apparent viscosity, and $\dot{\gamma}$ represents the shear rate.

TheBingham mode expression of the model is concise and clear, used to describe the relationship between the macroscopic viscosity of MRE and the external magnetic field. However, there are also certain limitations. Most models are used to describe linear shear stress and shear force relationships, which is not convenient for nonlinear models. With the continuous deepening of research on magnetorheological fluids, the nonlinear model formulais shown

$$\tau = \tau_m(H) + \eta_B \dot{\gamma}(1-\zeta\dot{\gamma}) \quad (2)$$

Where ζ represents nonlinear coefficient.

IV. ANALYSIS OF MICROSTRUCTURE MECHANISM OFMRE

According to the knowledge of electromagnetism, under the action of an external magnetic field, the magnetic particles are magnetized, resulting in a magnet. In this state, two poles are generated at both ends of the particles. The magnetic flux increment between the two poles of a particle is δH, Therefore, the expression for the magnetic force acting on the particle is

$$F_m = F_m^+ + F_m^- = Q_m \cdot \delta H \quad (3)$$

Where the magnetic charges at the N and S poles are Q_m^+ and Q_m^-, respectively.

Among them, the magnetic charge of a magnet is determined by the volume of magnetic flux and the surface density of the magnetic charge, which is not difficult to obtain

$$Q_m = \rho_m^s \cdot V_m = \mu_0 M \quad (4)$$

Where ρ_m^s is the magnetic surface density, V_m is the the volume of a magnetized object, μ_0 is the vacuum permeability,M is Magnetization.

The size of magnetic particles is on the micrometer scale, and it can be assumed that the directions of magnetic domains within the particles are consistent, resulting in the magnetic moment *m* of a magnetic particle with a volume

$$m = V_m M \quad (5)$$

By combining formulas (4) and (5), it can be obtained that

$$Q_m = \mu_0 M \cdot V_m \quad (6)$$

Then by combining formulas (3) and (6), it can be obtained that

$$\frac{F_m}{V_m} = \mu_0 M \cdot \delta H \quad (7)$$

Where the magnetic charge increment δH is a vector, the expression in the three directions is

$$\delta H = \left(a_x, a_y, a_z\right)\left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right) H = \left(a \cdot \nabla\right) H \quad (8)$$

Then by combining formulas (7) and (8), it can be obtained that

$$\frac{F_m}{V_m} = \mu_0 \left(M \cdot \nabla\right) H \quad (9)$$

The magnetic field size at a distance **r** from the magnetic field is

$$H = \frac{1}{4\pi\mu_0}\left(\frac{r_1}{r_1^3} - \frac{r_2}{r_2^3}\right) \quad (10)$$

The spatial structure of magnetic particles is shown in the Fig.3,$\mathbf{r_1}$ and $\mathbf{r_2}$ respectively represent magnetic field displacement vectors.

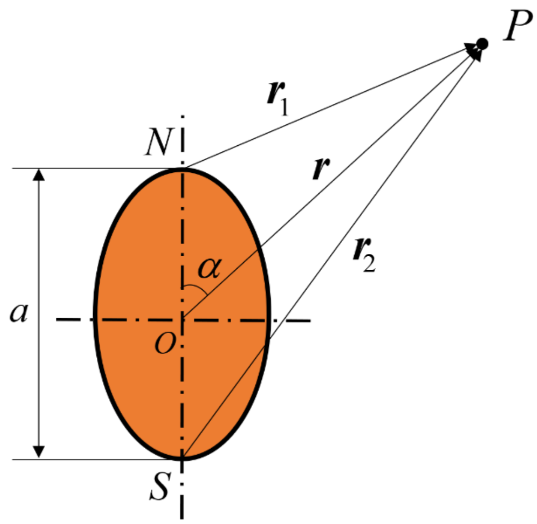

Fig.3 Magnetic field state of magnetized particles

By using vector superposition and approximate solution methods, and simplifying formulas

$$H = \frac{Q_m}{4\pi\mu_0 r^3}\left[\frac{3(r \cdot a)}{r^2} \times r - a\right] \quad (11)$$

When a is in the same direction as the magnetic moment **m**, the formula (11) can also be expressed as

$$H = \frac{Q_m}{4\pi\mu_0 r^3}\left[\frac{3(r\cdot m)}{r^2}\times r - m\right] \quad (12)$$

We obtained the magnitude of the magnetic field force on a single particle. By combining formula (12), it can be obtained that

$$F_m = \nabla(\mu_0 m\cdot H) \quad (13)$$

Expression of magnetic field energy

$$W_m = \mu_0 m\cdot H W_m = \mu_0 m\cdot\left\{\frac{1}{4\pi r^3}\left[\frac{3(r\cdot m)}{r^2}\times r - m\right]\right\} \quad (14)$$

Combining with Announcement 14, we can easily obtain the expression of the magnetic field energy betweenthei-th and j-th magnetic particles

$$W_{\mathrm{m}}^{ij} = \frac{\mu_0\left(3m_r^i m_r^j - m^i\cdot m^j\right)}{4\pi r_{ij}^3} \quad (15)$$

The formula (15) m_r^i、 m_r^j refer to the projection of the magnetic moments m^i、m^j of i and j magnetic particles in the direction r_{ij} .

The magnetic force generated between magnetic particles is along the position vector to generate magnetic field energy, so combining the energy rule with formulas (14) and (15), the magnetic force expression between different particles can be obtained

$$F_m^{ij} = \nabla\left[\frac{\mu_0\left(3m_r^i m_r^j - m^i\cdot m^j\right)}{4\pi r_{ij}^3}\right] \quad (16)$$

In practical use of magnetorheological fluid materials, the magnetic force on particles not only affects the external magnetic field, but also the mutual influence between particles after being magnetized. During service, magnetorheological fluid materials default to a uniform magnetic field, so the magnetic force on particles is mainly influenced by the mutual magnetic force between particles. According to formula (16), the magnitude of the magnetic force exerted on a single particle is equal to the sum of the magnetic forces exerted on the current particle by each particle.

The force distribution of magnetic particles is relatively complex, and the magnetic effects generated between magnetic particles are described in the above chapters. In addition, magnetic particles are also affected by the carrier liquid. During the dynamic evolution of magnetic particles into a chain like structure after being magnetized, the particles are subjected to viscous resistance from the carrier liquid, which can be given by the formula:

$$F_\eta = -6\pi R\eta v \quad (17)$$

Among them, η is the apparent viscosity of MRE, and v is the velocity vector of particle motion.

Magnetic particles are subjected to both viscous resistance and buoyancy, which is relatively simple and only affected by the density of the carrier liquid and the volume size of the magnetic particles. By default, the particles are spherical in shape, and the formula is as follows:

$$F = -\frac{4\pi R^3\rho_j}{3}g \quad (18)$$

In the formula, R is the particle radius, and ρ_j is the carrier density.

CONCLUSIONS

From the above work, we found that the magnetic field force exerted on magnetic particles is much greater than that exerted by viscous resistance, buoyancy, and gravity. Therefore, when studying the microscopic forces exerted on magnetic particles under external magnetic fields, we can ignore these forces. When there is no external magnetic field, this force will cause the MRE to settle.

The study of the microstructure dynamics mechanism of MRE in this work provides strong theoretical support for the rheological properties of MRE. This provides design and production guidance for the use of MRE in engineering applications.

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