Journal of Magnetism and Magnetic Materials 398 (2016) 137–140

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Normal force for static and steady shear mode in magnetorheological fluid

Xuhui Liu *, Dun Ye, Xiaoli Gao [1], Fang Li, Meng Sun, Hui Zhang, Tiangang Tu, Hao Yu

School of Mechanical Engineering, Shanghai Institute of Technology, 201418 Shanghai, China

ARTICLE INFO

Article history:
Received 4 November 2014
Received in revised form
31 August 2015
Accepted 2 September 2015
Available online 8 September 2015

Keywords:
Magnetorheological (MR) fluid
Normal force
Static mode and steady shear mode
Dynamic response

ABSTRACT

This paper presents the normal force phenomena for static and steady shear mode in magnetorheological (MR) fluid. The results of the study show that, in the static mode, with the magnetic flux density increasing, the normal force will increase until the maximum, and then reduce to a steady value, and during the increasing stage, it can be expressed as $F_N = 4667^*B^{2.48}$ approximately; however, in the steady shear mode, only when the magnetic flux density achieves a certain value, the normal force phenomena will be observed clearly, and with the increasing of magnetic field, the normal force reaches the maximum, and then also decreases to a steady value. Besides, by defining the time parameters of dynamic response, the dynamic response of normal force is studied. If the shear plate is stationary, from the magnetic field on to a stable normal force produced, the response time is about 25.11 ms.

1. Introduction

Magnetorheological (MR) fluid is a kind of intelligent material, which consists of the magnetizable particles, carrier liquid and surfactant. It can transform from the free flow state to half solid or solid state under the conditions of the applied magnetic field, however, once the magnetic field is off, it will recover to the free flow state, and the transformation will be completed in several milliseconds [1,2], which is called MR effect. As the solid–liquid composite material, its magnetic properties are diverse due to some conditions such as temperature [3] and mixed solid–liquid ratio. Many researchers [4–6] have focused on the MR technology in recent years, such as the mechanical devices like the semi-active controllable damper, clutch and actuators. As mentioned above, the reason of MR effect produced is mainly due to the movement of magnetizable particles, that is to say, when a certain magnetic field applied, the shape of the gathered magnetizable particles will appear as the chain-like, columnar and other cluster parallel to the magnetic flux density vector [7,8]. This behavior will cause the surprised shear yield stress when MR fluid is applied in shear mode [9], besides, the normal force along the direction of the magnetic field is also accompanied with the shear force (or the shear stress), and it is also reversibly controllable by adjusting the external magnetic field.

In recent years, some researchers have focused on the characteristics of MR fluid (or MR elastomer) along the direction of the magnetic field, they mainly concentrated in the normal force produced by the positive pressure. Gong [10,11] found, under compression status, the magnetic-field-induced normal force of MR elastomer will increase with the increasing of magnetic field and precompression force. As to the shear mode, Yu [12] investigated the normal force of MR gel, their experimental results indicated that the magnetic field had a greater impact on the normal force of MR gel, and the increment of magnetic field enhanced the normal force obviously, however, as the big difference in the essential characteristics for the MR fluid and MR gel, such as the flow viscosity, the surfactant, even the mass content of magnetic particles, which makes it quite important for the design of test rig and measurement methods. Thus, the further investigation on the normal force of MR fluid will be more interesting and necessary.

In the action of magnetic field, the magnetic particles in MR fluid will rearrange along the direction of the magnetic field to produce the normal force (or normal stress), the relationship between the normal force and magnetic induction intensity based on plate–plate is closed to the exponent of 2.6 [13]. But in the shear strain, the experimental results have some contradictions, such as De Vicente [14] found that the normal stress will produce only in some cases of shear strain, and it will increase with the shear strain first, and then start to decline to a certain value, and Modesto [15] and others show the normal stress will decrease with the increase of shear strain, besides, even in the absence of shear strain, the normal stress will also occur. Wong [16] has also shown some different results, that is, with the increase of shear strain, the normal stress will increases to a certain limit.

* Corresponding author.
E-mail address: liu_xuhui79@163.com (X. Liu).
[1] The author contributed equally to this work and should be regarded as co-first author.

http://dx.doi.org/10.1016/j.jmmm.2015.09.009
0304-8853/

In this paper, for the sake of the further investigation on the normal force of MR fluid, a set of test rig based on plate–plate shear is built, and the materials of magnetic circuit, DC motor and force sensor is also selected in the static and steady shear mode. The designed test rig is different from the previous test method, here, in order to reduce the influence of magnetic attraction between the two shear plates on the normal force; the lower shear plate is made of non-magnetic copper. In the static and steady shear mode, the effect of external magnetic flux density, shear rate on the normal force is studied experimentally, the expression for the produce normal force and the magnetic flux density is obtained; by defining the time parameters of dynamic response, the dynamic response of normal force for the static and steady shear mode is also investigated.

2. Experimental materials

MR fluid used in the experiment is MRF-J01T, which is composed of magnetizable particles in micron-size, hydrocarbon based oil and other additives, and provided by the Chongqing Instrument Materials Institute, China. Its density is 2.65 g/cm^3, the viscosity of the specimen at zero magnetic field is 0.8 Pa s ($\gamma = 10\ s^{-1}$, 20 °C), and the volume fraction of solid magnetic particle (mainly carboxyl iron) is about 30%. The magnetizable particles are observed by scanning electron microscopy (SEM) and as shown in Fig. 1, they can be viewed as spherical with typical dimensions of around 1–5 μm in diameter. The dynamic yield stress vs. magnetic flux density is measured under the shear rate of 10 s^{-1}, and as shown in Fig. 2, it can be obtained that the shear yield stress can arrive at 53 kPa when the magnetic flux density is 0.32 T.

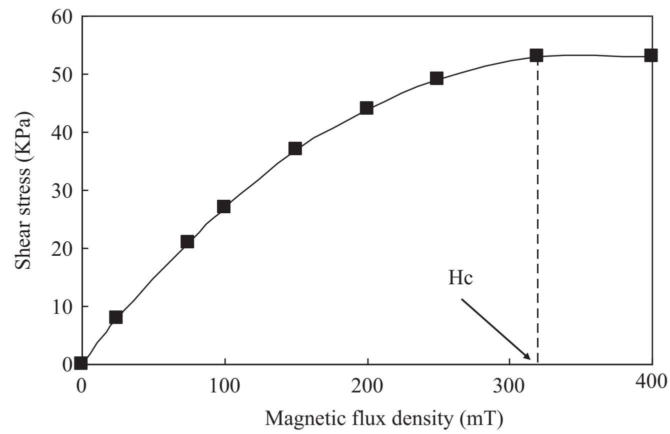

Fig. 2. Shear stress vs. magnetic flux density.

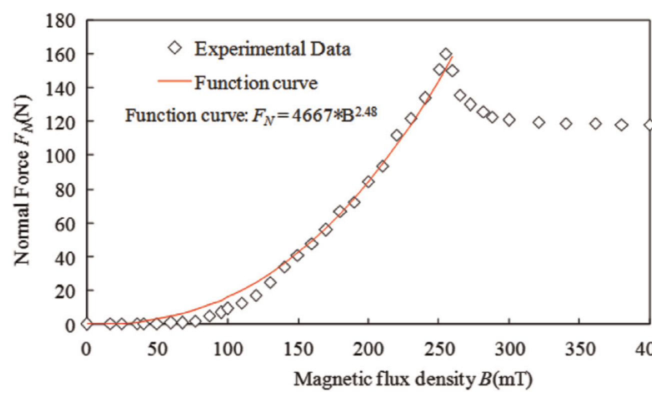

Fig. 3. Normal force vs. magnetic flux density.

3. Results and discussion

3.1. Experimental results in static mode

In this section, experimental result is obtained when the shear plate keeps static. The different normal force in MR fluid is observed by changing the excitation current in the coil. Firstly, MR fluid is full of the shear gap, and the normal force under different magnetic field intensity is measured by the test system mentioned above. As the change of normal force is very clear, thus, only when the value of the normal force is steady approximately, the collected data on normal force is considered valid. After elimination of interference factors as soon as possible, the normal force vs. magnetic flux density is obtained finally.

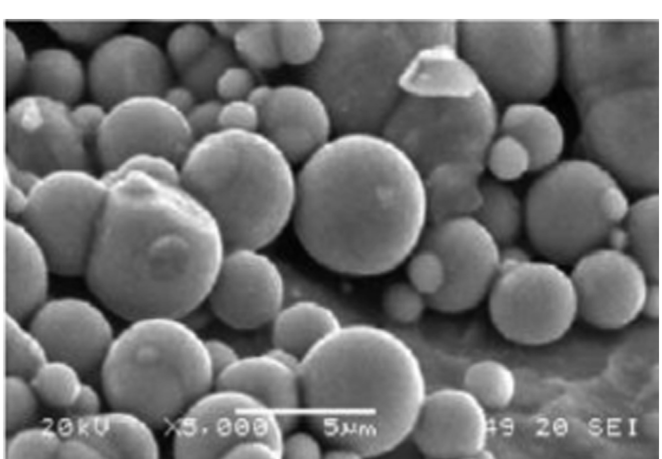

Fig. 1. Magnetic particle (SEM).

As shown in Fig. 3, when the magnetic flux density is less than 260 mT, the normal force increases with the increasing magnetic field. By curve fitting, when the magnetic flux density is less than 260 mT, the experimental curve fits the relationship $F_N \propto B^{2.48}$ perfectly. Compared with the results provided by See [13], the index have a little difference, which maybe results from the different MR fluid sample, besides, the different testing method will also have influence on the testing results. By using MATLAB software, the normal force of the used sample is consistent with the following Eq. (1).

$$F_N = 4667*B^{2.48} \tag{1}$$

Furthermore, it is noteworthy that, when the magnetic flux density arrives around 260 mT, there occurs a sudden decline on the normal force. After repeated, the occurred decline is confirmed. In order to explain the phenomena on the decline of normal force in MR fluid, the mechanism of generated normal force is analyzed.

It can be seen from Fig. 4, when magnetic field is applied on MR fluid, the attractive force will produce among the magnetic dipoles, thus, the magnetized spherality particles will also array like the chains (or columns) along the direction of magnetic flux density. The forming-chain effect will give rise to some spherical particles squeezing into the existing chains, which makes the chains or chain structures extend along the field direction. When all of available particles form the chains or clusters, the normal forces will no longer increase, that is, all of the magnetic particles in MR fluid have been magnetized. Considering the principle of minimum magnetic field energy, when the magnetic field continues to increase, these magnetized chains or clusters are