

The effect of friction on magnetorheological fluids

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Abstract

This paper presents an experimental approach to study the effect of friction on magnetorheological (MR) fluids. Both steady and dynamic modes were employed to investigate MR fluid behaviors. The experimental results indicate that the total MR effects are dominated by two factors: magnetic force and friction force. Conventionally, the magnetic force contribution to MR effect has been intensively studied while the friction force effect has attracted less attention. This study provides a method to quantitatively predict the friction contribution to the total MR effect. It may be used to effectively analyze enhanced MR effects reported by other groups. Also, it might provide good guidance to develop high-efficiency MR fluids.

Keywords : magnetorheological fluids, friction effect

1. Introduction

Magnetorheological (MR) fluids consist of suspensions of micro size magnetic particles in a liquid carrier such as oil or water. They are free-flowing media whose flow properties change rapidly and reversibly under the influence of a magnetic field. The resulting MR effect corresponds to the increase in shear stress due to a magnetic field. MR fluids have found applications in commercial devices such as clutches, shock absorbers and other mechanical-electrical coupling devices (Hitchcock *et al.*, 2007; Li *et al.*, 2000; Li and Du, 2003).

The efficiency of an MR fluid is evaluated through its yield stress, which measures the strength of the structure formed by the application of the field. A number of models have been proposed to describe the yield stress of MR fluids. Rosensweig (1995) proposed a mean field continuum model to calculate the static yield stress of MR fluids. Bossis *et al.* (1997) calculated the yield stress of a MR suspension based on a mesoscopic description of the structure and a microscopic approach of the interparticle forces. By taking magnetic non-linearities and saturation into account, Jolly *et al.* (1996) developed a quasi-static, one-dimensional model to examine both mechanical and magnetic properties of MR materials. Ginder *et al.* (1996) used non-linear finite element method, by taking the effect of magnetization saturation into account, to calculate the field distribution in chains of magnetizable particles and the interparticle attractive force, and consequently to predict

the magnitude of the field-dependent shear stress. Tang and Conrad (2000) calculated the static yield stress of MR fluid with a two-dimensional laminar structure model using the Maxwell stress tensor and taking into account the field concentration between the particles inside the aggregates and the effect of saturation magnetization of the particles.

The above models are generally based on the calculation of inter-particle forces, which can predict the right order of magnitude of the yield stress in some cases. However, these models cannot be effectively to predict enhanced MR fluids, reported by Tang, Tao and their co-workers (Tang *et al.*, 2000; Tao, 2001). Tang *et al.* (2000) developed a device, which was used to compress the MR fluid along the field direction immediately after a magnetic field is applied. This process did improve the yield stress upper to a limit well above 800 kPa. They ascribed the enhancement to the change of microstructure due to the compression effect. Zhang *et al.* (2004) extended Tang's work (2000) to study the mechanism of the squeeze-strengthen effect of MR fluids. They claimed that the friction effect should be taken into account besides the local field effect. To verify the effect of compression, See *et al.* (2006) used a MR rheometer to measure viscoelastic properties, particularly the storage modulus, of MR fluids under compression. They found that the compression did not have a large effect on the MR response. Though Zhang *et al.* (2004) concluded that the total MR effect was composed of magnetic dipoles' interact force and friction, they didn't give further study on how to quantitatively predict these two effects. In literature, there is very few report to discuss this problem. This paper aims to quantitatively predict the contribution of friction and magnetic interaction force by

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studying rheological properties of MR fluids under both steady and dynamic working conditions. The result is expected to give a good explanation of the discrepancy between Tang *et al.*'s (2000) and See *et al.*'s (2006) work.

2. Modeling and Experimental

2.1. Modeling

Viscoelastic properties of ER fluids were theoretically and experimentally investigated by Jordan and his collaborators (McLeish *et al.*, 1991; Jordan *et al.*, 1992). The mechanisms contributing to the dissipated energy in ER fluid can be hydrodynamic force due to the particles' or chains' motion in media, the media flow (*i.e.* fluid friction), or the interparticle friction. As an analog of ER fluid, similar mechanisms also probably contribute to the dissipated energy in MR fluid. The overall or general friction force could be composed of different contributions of these effects. It is known that the hydrodynamic force depends on the relative velocity between particles and media while the interparticle friction depends on the normal force and friction factor. In a quasi-static shear at a low rate or a low oscillation frequency, the interparticle friction provides a dominate role as the hydrodynamic force can be neglected at such very small velocity cases compared with notable normal force in MR fluids. Therefore, the modeling approach is based on the assumption that the field induced shear stress of MR fluid is composed of the inter-dipole stress due to magnetic force and the friction stress.

Fig. 1 shows a pair of iron particles, where the upper particle slides in the shear direction. The resulting shear stress has two components, magnetic induced stress, τ_m , and friction induced stress, τ_f , between particles. The magnetic induced shear stress, τ_m , is derived from the dipoles' interaction stress σ and it is accompanied by a storage of magnetic energy within the structure of the particles, while the

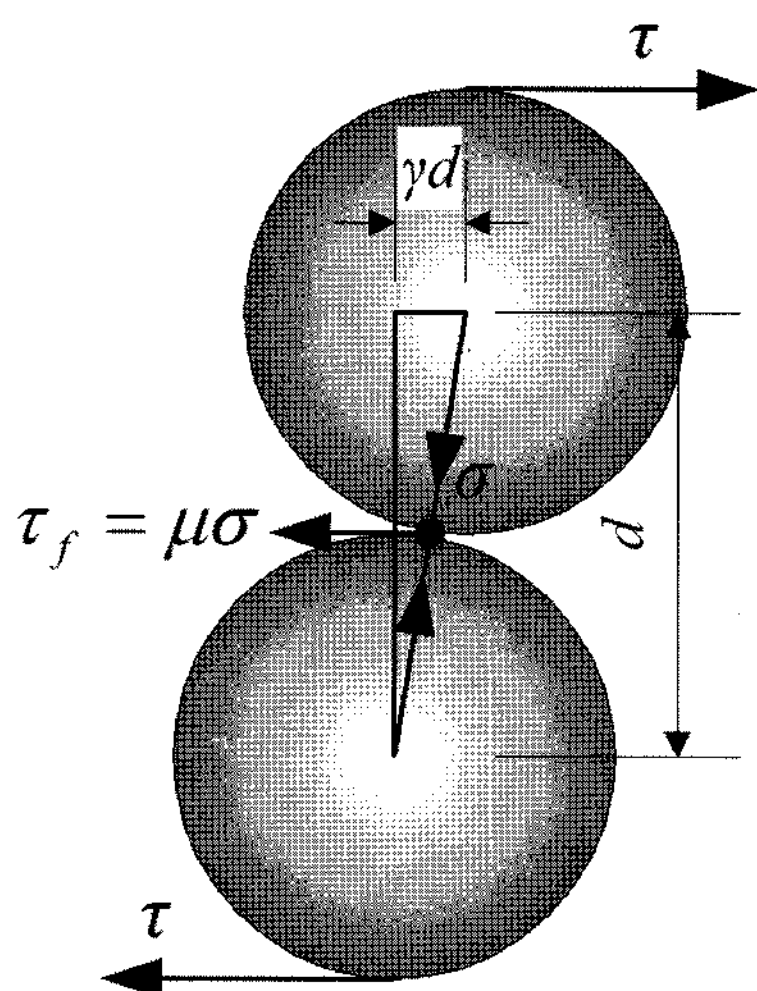


Fig. 1. A pair of particles in shear.

friction stress, τ_f , is associated with a continuous input of dissipation energy. The friction stress is a product of the interaction stress σ and the particle's surface friction coefficient, *i.e.* $\tau_f = \mu\sigma$. When the external shear stress is removed, the slid particle undergoes a partial recovery as the magnetic energy is recovered; while the energy due to friction is unrecovered.

2.2. Experimental

A commercial MR fluid, MRF-132AD, supplied by the LORD Corporation is chosen as the sample. The solids content by weight is 80.98% (LORD Technical Data). Its rheological properties were measured by using a MR rheometer (MCR 301, Anton Paar Companies, Germany). The rheometer is equipped with an electromagnet kit, which can generate a magnetic field, perpendicular to the shear flow direction. A parallel-plate measuring system with a diameter of 20 mm at a gap of 1 mm was used. The magnetic fields used in this study vary from 0 kA/m to 600 kA/m.

Under steady-state shear with the shear rate ranging from 0.01 to 100 rad/s, the dependency of shear stress on shear rate for the MR fluid exposed to various magnetic fields where measured, as shown in Fig. 2. Similar results have been reported by many groups (Bossis *et al.*, 1997; Wang and Gordaninejad, 1999), and both the simple Bingham plastic model and the Herschel-Bulkley model were used to effectively predict such behavior (Wang and Gordaninejad, 1999). The stress-strain relationship of MR fluids under various magnetic fields were measured and shown in Fig. 3(a), where the strains applied vary from 0 up to 50%. These results demonstrate again that MR fluid behaviors have two regimes: pre-yield regime and post-yield regime, which are generally separated by a yield strain, γ_y , (Li *et al.*, 2003). At the pre-yield regime, MR fluids are modeled as linear viscoelastic solid, where shear stress shows a linear relation with shear strain and the slope of stress-strain curve is the shear modulus. It is supposed that the shear modulus increases steadily with the increase of magnetic field before the MR fluid reaches saturation status. At the

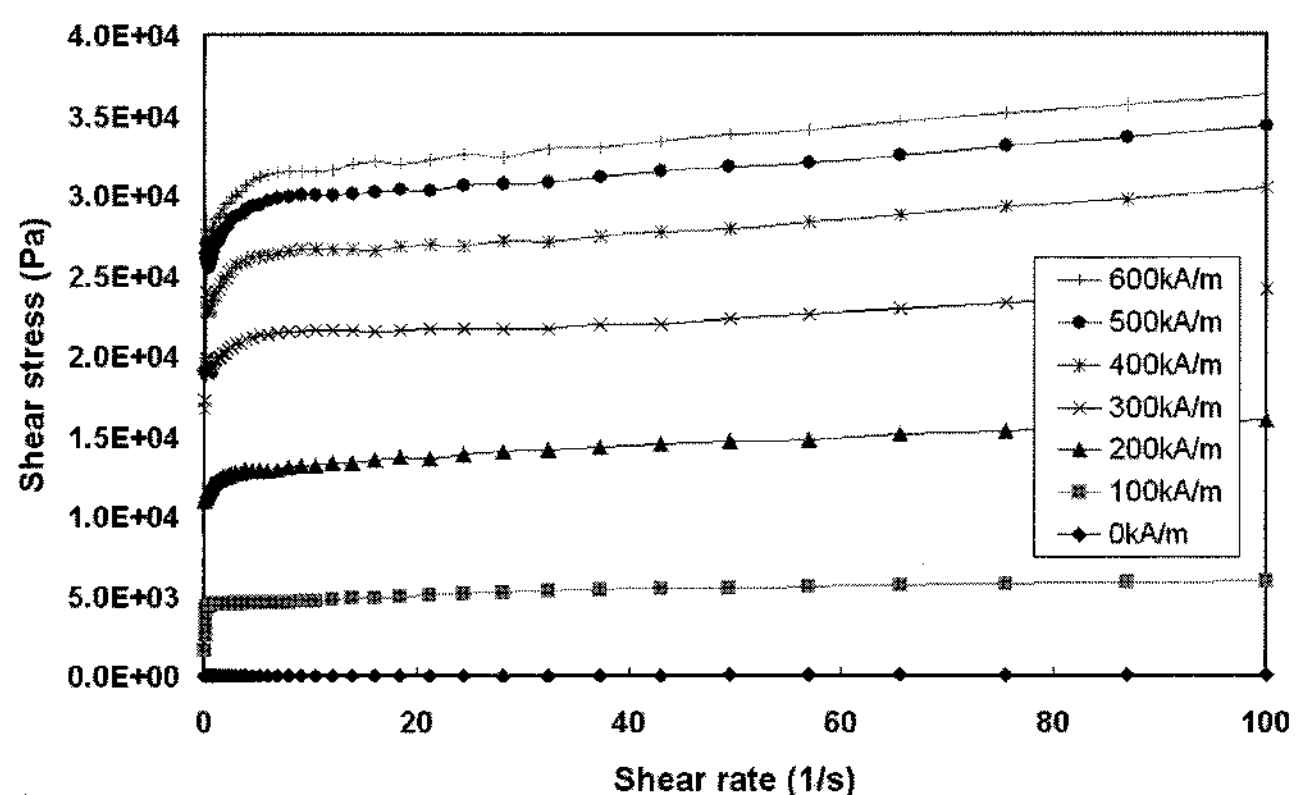
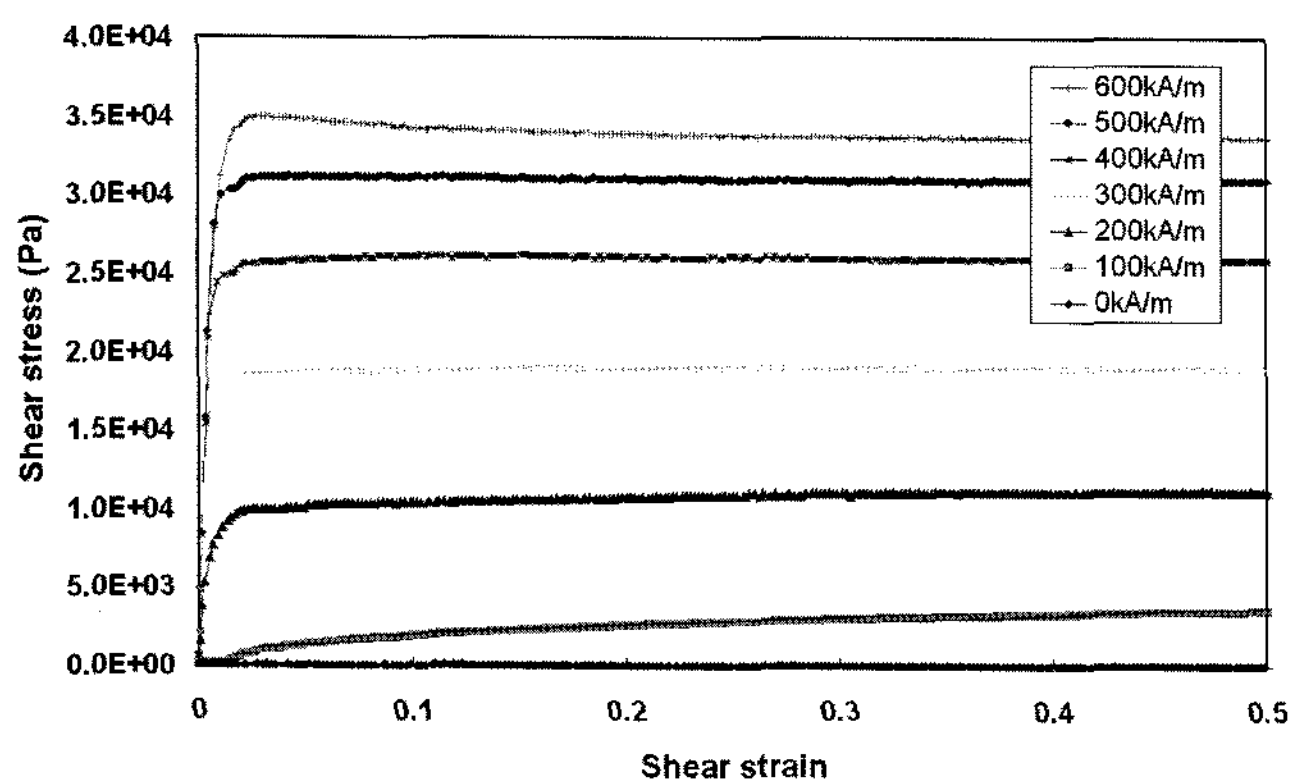
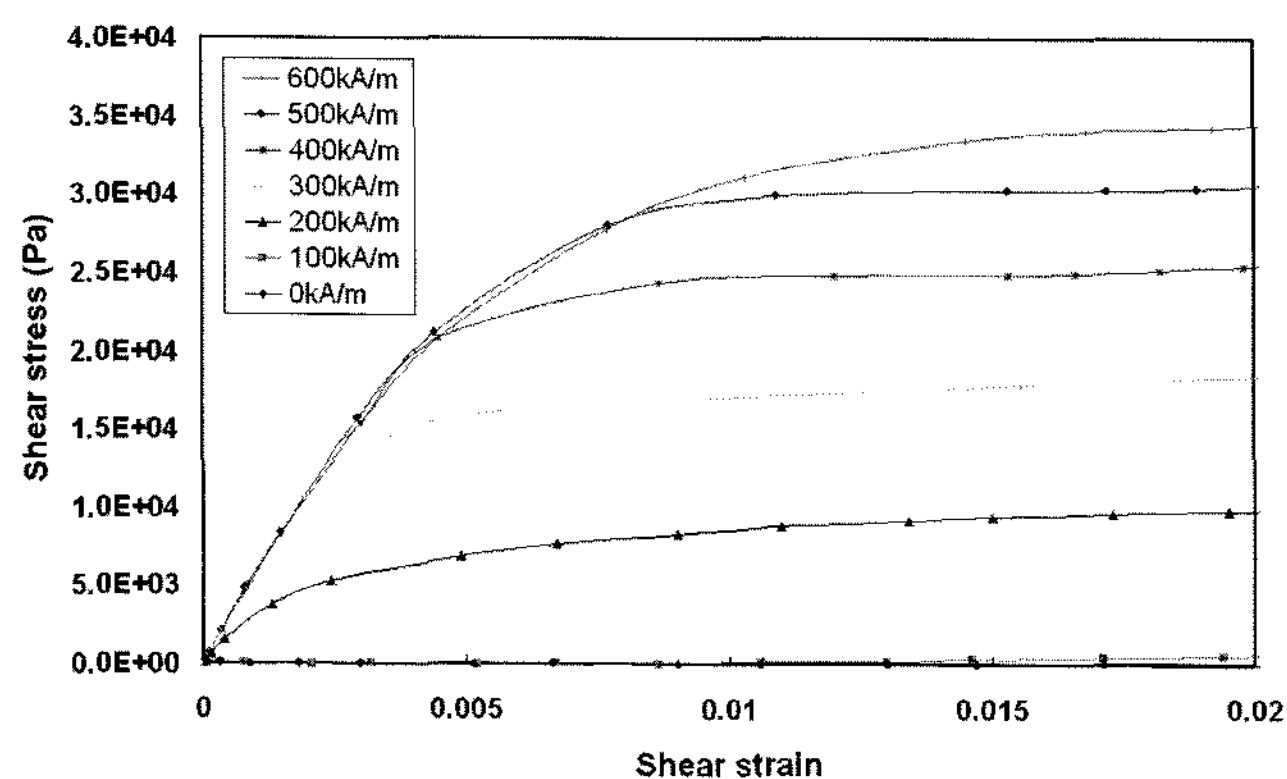


Fig. 2. Shear stress versus shear rate at different magnetic fields.



(a)



(b)

Fig. 3. Shear stress versus shear strain at different magnetic fields.

post-yield regime, shear stress is independent of strain. Further examining the pre-yield regime behavior with sufficiently small strain, as shown in Fig. 3(b), it is found that the linear relationship between shear stress and shear strain is less than 0.3%. As the shear strain at conventional working conditions is much larger than this yield strain, so the linear shear stress versus shear strain relationship at pre-yield regime is not sufficient to cover overall performances of MR fluids. Also, the results from steady shear measurement cannot give distinct information on the magnetic and friction contribution. Furthermore, the conventional theory on the shear stress-strain curve cannot effectively predict the stress-strain relationship as they don't take the friction into account.

Again in Fig. 1, the shear rate dependence of shear stress is composed of two parts: one is from magnetic stress and the other is from friction. However, it would be hard to find specific contributions of these two parts just based on steady state experiment. To measure the magnetic induced contribution exactly, oscillatory shear is used to test samples, where both storage modulus, G' , and loss modulus, G'' , at various magnetic fields can be obtained. It is known that the storage and loss modulus in viscoelastic materials can be used to separately measure the stored energy (rep-

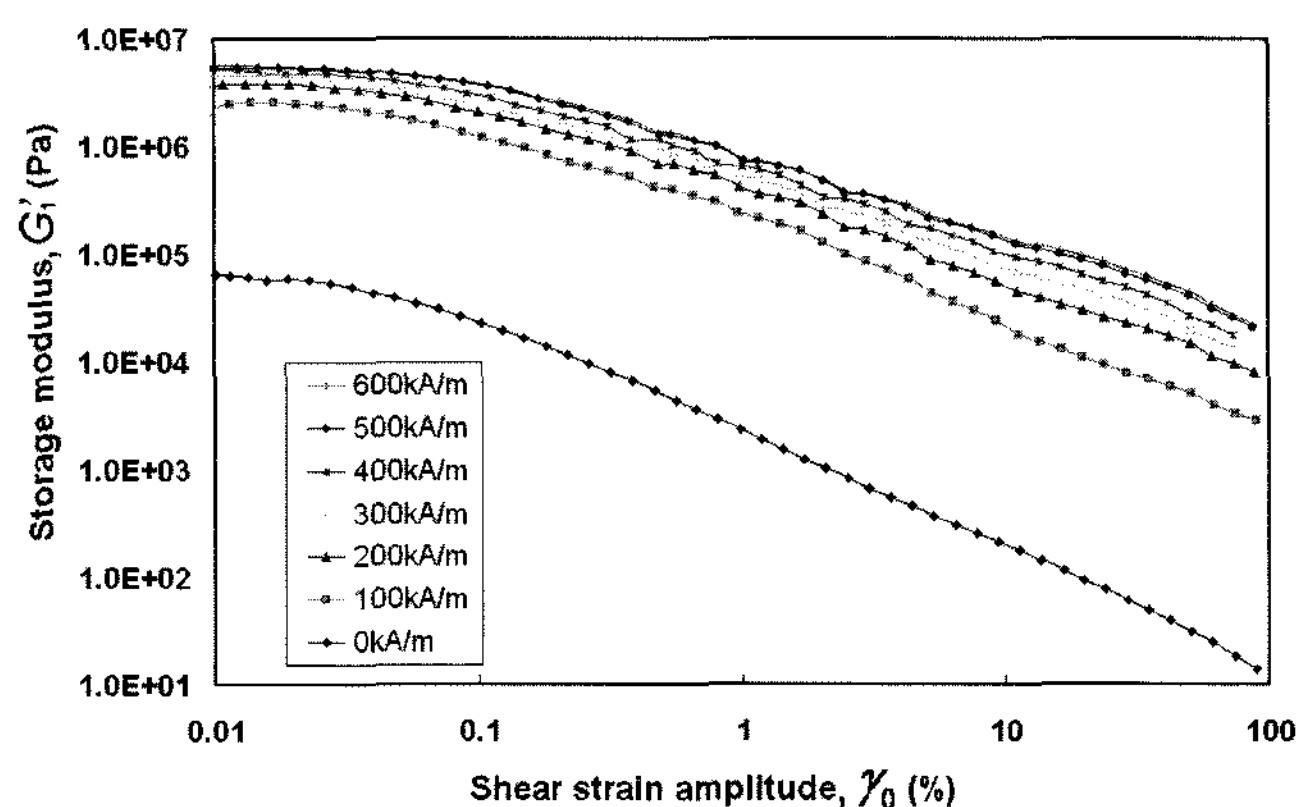


Fig. 4. The storage modulus of MR fluid at different magnetic fields.

resenting the elastic portion) and the energy dissipated as heat (representing the viscous portion). Here the elastic part can be looked as the magnetic induced part, because they are the energy stored in the material. And the viscous part can be looked as the friction part, because they are the energy dissipated as heat. Therefore, in this paper, the storage modulus, measured by using oscillatory shear, is used to quantitatively determine the elastic part. Fig. 4 shows the experimental results of the storage of MR fluid at various magnetic field intensities. These results also demonstrate that MR fluid shows linear viscoelastic properties at sufficient small strain amplitudes, where the storage modulus is independent of shear strain. At high strain amplitudes, the storage modulus decreases steadily with the increase of strain amplitude. By using the equation $\tau_{\text{elas}} = G' \gamma$, the shear stress due to storage modulus is calculated and shown in Fig. 5. Comparing Fig. 5 and Fig. 3(a), it is found that the shear stress due to storage part, or the magnetic force between particles, is lower than the total shear stress. The results demonstrated that the total shear stress indeed composed of friction contribution. The difference between these two parts is the shear stress contribution due to friction. Similar result has been reported on ER fluid,

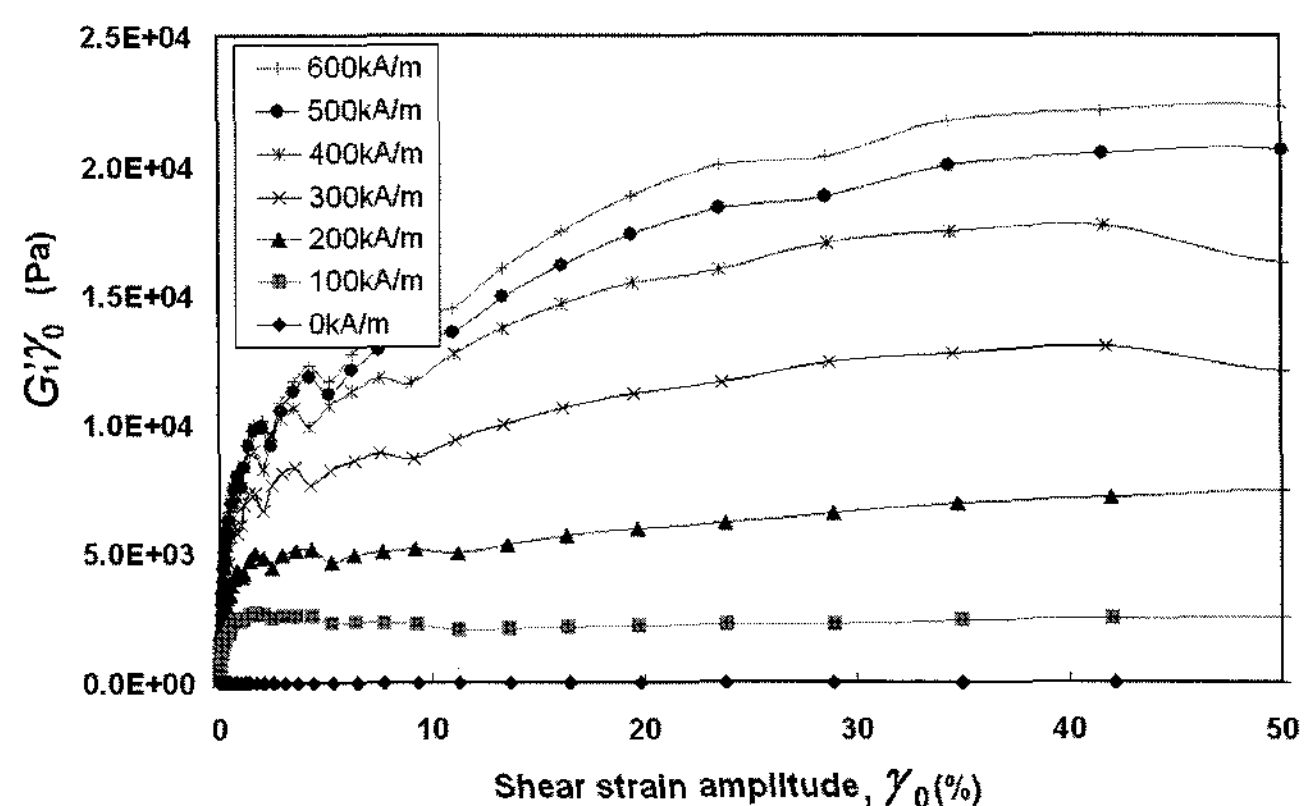


Fig. 5. The shear stress due to storage energy versus shear strain in different magnetic field.

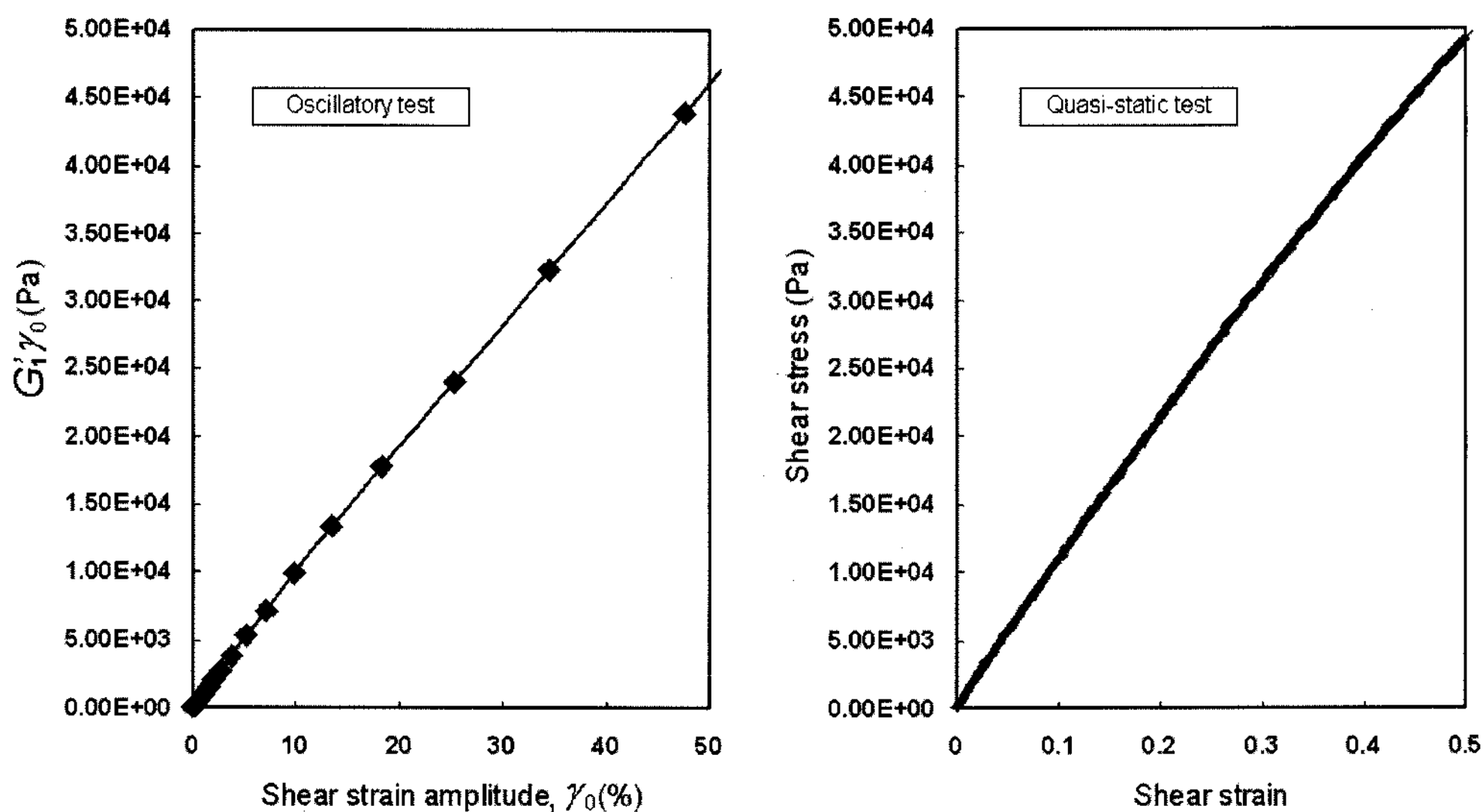


Fig. 6. The comparison between oscillatory and quasi-static test results of PDMS.

shear stress of which was separated into attractive ER force and destructive viscous hydrodynamic force (Cho *et al.*, 2003). To verify this assumption, or to compare experimental results obtained using two different testing methods, oscillatory shear and steady shear, a viscoelastic sample of silicon rubber, Polydimethylsiloxane (PDMS) 2025 (Dow coming 184) was prepared, which is a room-temperature vulcanizing elastomer with a transparent appearance. Fig. 6 shows the strain-stress curves tested using these two methods. It can be observed that experimental results from both these two methods are very close. The reason for this is probably that this material has relatively low inner friction (its damping factor is about 0.03). This result may strongly support our assumption that the friction contribution is the major reason for the wide difference between oscillatory and quasi-static test results of MRF.

From the oscillatory shear result (Fig. 5), the MRF sample has strain dependent properties until about 0.4. This phenomenon also reflected in the proposed empirical equation (1). For the steady shear result, shear stress is independent strain when the strain is above 0.3%. The value difference between oscillatory and steady shear is considered as the friction force. The storage modulus of MRF is derived from magnetic force, *i.e.*, inter-dipole force. According to the relationship between the normal force (the inter-dipole force) and the friction force, the coefficient of friction 0.2 is achieved. An empirical equation was derived to predict the shear stress of this MR fluid:

$$\tau = \tau_f + \tau_m = \mu\sigma + \gamma\sigma \approx \begin{cases} (\mu + \gamma) \frac{0.3H}{1 + 5\gamma} & \gamma \leq 0.4 \\ (\mu + 0.4)0.1H & \gamma > 0.4 \end{cases} \quad (1)$$

Here $\mu \approx 0.2$ is the coefficient of friction. The normal stress

due to the field-dependent inter-dipole force is σ .

From Eq. (1), it can be found that the friction stress plays a dominant role in contributing to the total shear stress at sufficiently small strain. For high shear strain, it contributes to about 30% of the total stress.

3. Discussion

Eq. (1) provides an empirically quantitative equation to predict the friction effect, which may be used to explain the discrepancy between Tang's and See's work (Tang *et al.*, 2000; See *et al.*, 2006). See *et al.* (2006) measured the storage modulus of MR fluids under different compression gaps and found there was no obvious change of the storage modulus. This is right as the storage modulus reflects the capability of storing energy. The small compression effect won't increase energy storing capability. However, the gap compression would increase the surface friction characteristics, which would increase the shear stress due to friction. It is noted that the compressive pressure in Tao's (2001) experiment is up to 2.5 MPa, and the yield stress induced under a constant field increased dramatically from approximately 100 kPa to over 600 kPa. Suppose the coefficient of friction in Tao's experiment is the same as the value of 0.2 what we experimentally obtained, the shear stress due to the compression is calculated as $\tau_f = 0.2 \times 2.5 \text{ MPa} = 500 \text{ kPa}$. This value is in good agreement with the experimental results by Tao and their co-workers (Tang *et al.*, 2000; Tao, 2001). So we propose the enhanced MR effect by Tang and Tao actually comes from friction effect rather than magnetic forces. Modeling approach shows that the shear modulus is proportional to the interactive forces between particles. The interactive forces show a sharply decreasing trend with the particle distance to the order of 3. Therefore, decreasing particle gap or dis-

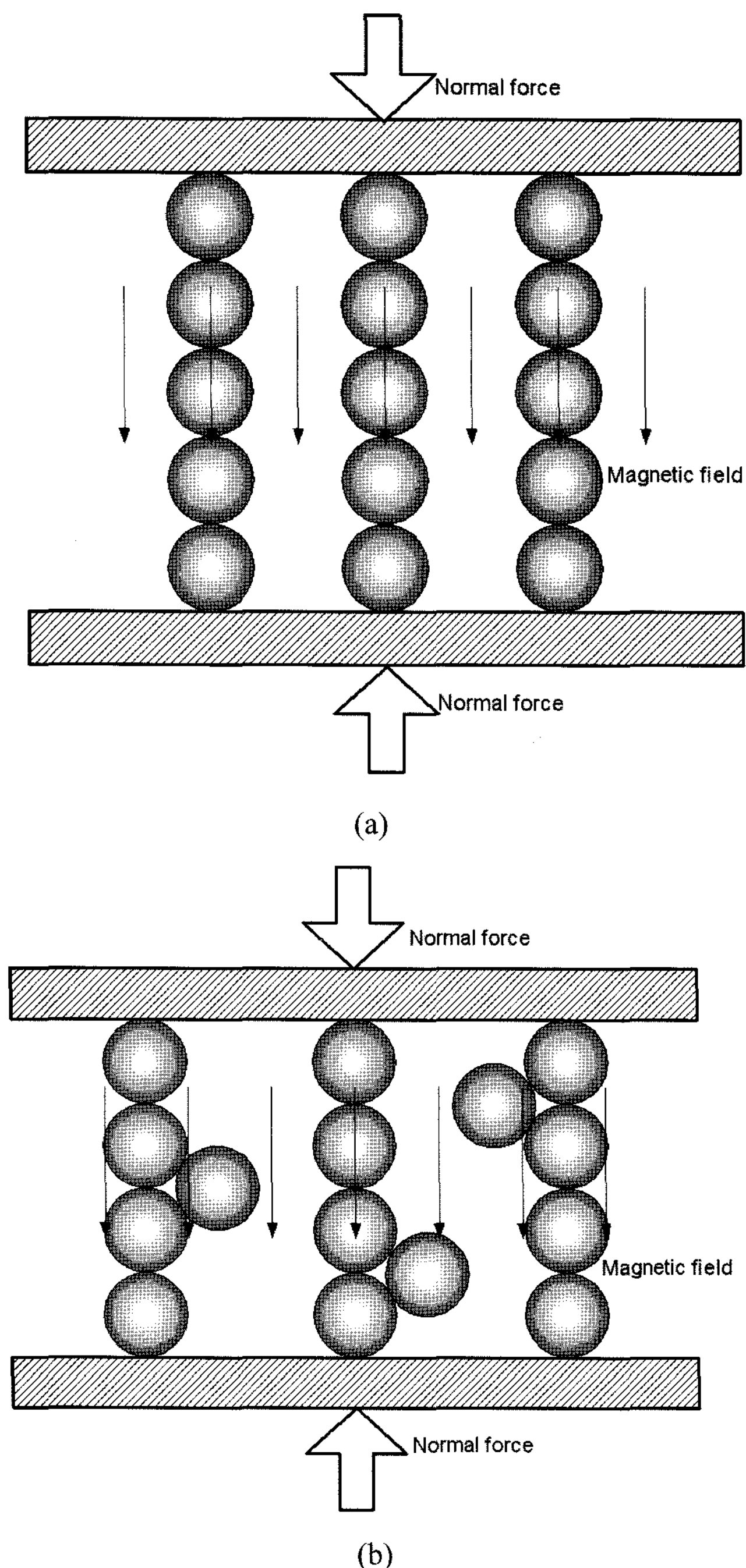


Fig. 7. The particle chains under compression.

tance would significantly increase the shear modulus. However, when the particle volume is high, where all particles form into stable chains, as shown in Fig. 7(a), under the compression, there is no space for the particle to move along the chain direction. These particles can only be moved to side space, as shown in Fig. 7(b). The interactive forces for these two cases are very similar. This explanation could support See *et al.*'s experimental results. However, at the case Fig. 7(b), the surface pressure at the compression case is higher than that of case a, the friction is higher than the case a, so the total MR effect shows an

increasing trend. That could be the reason why Tang *et al.*'s experiment shows a higher MR effect. The analysis might also be helpful to produce new MR fluids.

It is known that the maximum shear strength of MR fluids is proportional to the square of the saturation magnetization of the particles. It is widely thought that MR fluids with higher yield stresses can only be produced when new materials possessing larger saturation value are identified. The analysis indicates that the shear stress of MR fluids can also be improved if the friction factor of particles is improved. To this end, finding materials or processes to increase friction factors could be good approaches to enhance MR effects. The friction factor could be conceivably improved by using some pre-treatment for particles, such as fabricating the particles with the materials have higher coefficient of friction, coating the particles with other gum-like materials. Wen *et al.* (2003) used coated nanoparticles to fabricate giant electrorheological with a yield stress up to 130 kPa, breaking the theoretical upper bound on conventional ER static yield stress. Wu *et al.* (2006) used carbonyl iron powders coated with guar gum as magnetic particles in the MR fluid. Experimental results showed that inducing a guar gum strengthened the yield stress of the MR fluid. Their results could be due to the increment of friction part. On the other hand, particles' coating shell with low friction factor may decrease the MR effect. Cho *et al.* (2004) and Jang *et al.* (2005) reported carbonyl iron particles coated with either PMMA or PVB, which have smoother surface, indeed decreased MR effect while increasing the dispersion stability. Lower friction factor and increased particle distance due to polymeric coating may be the reasons for MR effect decrease.

4. Conclusion

In this paper, the rheological behavior of MR fluids was tested by quasi-static, steady and dynamic shear mode. The effect of compression on the MR effect was quantitatively investigated by comparing the stress difference between two testing methods. At low shear strain conditions, resulting stress due to the friction plays an important role in the overall resulting stress; at large shear strain conditions, its contribution is about one third of overall shear stress, so the contribution of friction can not be neglected in most cases. This investigation provides a reasonable explanation of the disagreement of the recent reports. It would also provide good guidance to develop new MR materials.

References

- Bossis, G., E. Lemaire, O. Volkova and H. Clercx, 1997, Yield stress in magnetorheological and electrorheological fluids: a comparison between microscopic and macroscopic structural models, *Journal of Rheology* **41**(3), 687-704.

- Cho, M. S., Y. H. Cho, H. J. Choi and M. S. Jhon, 2003, Synthesis and electrorheological characteristics of polyaniline-coated poly(methyl methacrylate) microsphere: size effect, *Langmuir* **19**, 5875-5881.
- Cho, M. S., S. T. Lim, I. B. Jang, H. J. Choi and M. S. Jhon, 2004, Encapsulation of spherical iron-particle with PMMA and its magnetorheological particles, *IEEE Transactions on Magnetics* **40(4)**, 3036-3038.
- Ginder, J. M., L. C. Davis and L. D. Elie, 1996, Rheology of magnetorheological fluids: models and measurements, *International Journal of Modern Physics B* **10(23-24)**, 3293-3303.
- Hitchcock G. H., X. J. Wang and F. Gordaninejad, 2007, A new bypass magnetorheological fluid damper, *Journal of Vibration and Acoustics-Transactions of the ASME* **129(5)**, 641-647.
- Jang, I. B., H. B. Kim, J. Y. Lee, J. L. You, H. J. Choi and M. S. Jhon, 2005, Role of organic coating on carbonyl iron suspended particles in magnetorheological fluids, *Journal of Applied Physics* **97**, 10Q912-1-10Q912-3.
- Jolly, M. R., J. D. Carlson and B. C. Munoz, 1996, A model of the behavior of magnetorheological materials, *Smart Materials and Structures* **5**, 607-614.
- Jordan, T. C., M. T. Shaw and T. C. B. McLeish, 1992, Viscoelastic response of electrorheological fluids. II. field strength and strain dependence, *Journal of Rheology* **36(3)**, 441-463.
- Li W. H., G. Z. Yao, G. Chen, S. H. Yeo and F. F. Yap, 2000, Testing and steady state modeling of a linear MR damper under sinusoidal loading, *Smart Materials and Structures* **9(1)**, 95-102.
- Li, W. H. and H. Du, 2003, Design and experimental evaluation of a magnetorheological brake", *International Journal of Advanced Manufacturing Technology* **21(6)**, 438-445.
- Li, W. H., H. Du, G. Chen, S. H. Yeo and N. Guo, 2003, Non-linear viscoelastic properties of MR fluids under large-amplitude-oscillatory-shear, *Rheologica Acta* **42**, 280-286.
- McLeish, T. C., B. T. Jordan and M. T. Shaw, 1991, Viscoelastic response of electrorheological fluids. I. frequency dependence, *Journal of Rheology* **35(3)**, 427-448.
- LORD technical data, MRF-132DG magneto-rheological fluid, <http://www.lordfulfillment.com/upload/DS7015.pdf>.
- Rosensweig, R. E., 1995, On magnetorheology and electrorheology as states of unsymmetric stress, *Journal of Rheology* **39(1)**, 179-192.
- See, H., S. Mackenzie and B. T. Chua, 2006, Effect of compression on the response of a magneto-rheological suspension, *Korea-Australia Rheology Journal* **18(3)**, 121-126.
- Tang, X. L. and Conrad, H., 2000, An analytical model for magnetorheological fluids, *Journal of Physics D-Applied Physics* **33(23)**, 3026-3032.
- Tang, X., X. Zhang, R. Tao and Y. M. Rong, 2000, Structure-enhanced yield stress of magnetorheological fluids, *Journal of Applied Physics* **87(5)**, 2634-2638.
- Tao, R., 2001, Super-strong magnetorheological fluids, *J. Phys.: Condens. Matter* **13**, R979-R999.
- Wang, X. J. and F. Gordaninejad, 1999, Flow analysis of field-controllable, electro- and magneto-rheological fluids using Herschel-Bulkley model, *Journal of Intelligent Material Systems and Structures* **10(8)**, 601-608.
- Wu, W. P., B. Y. Zhao, Q. Wu, L. S. Chen and K. A. Hu, 2006, The strengthening effect of guar gum on the yield stress of magnetorheological fluid, *Smart Materials and Structures* **15(4)**, N94-N98.
- Wen, W. J., X. X. Huang, S. H. Yang, K. Q. Lu and P. Sheng, 2003, The giant electrorheological effect in suspensions of nanoparticles, *Nature Materials* **2(11)**, 727-730.
- Zhang, X. Z., X. L. Gong, P. Q. Zhang and Q. M. Wang, 2004, Study on the mechanism of the squeeze-strengthen effect in magnetorheological fluids, *Journal of Applied Physics* **96(4)**, 2359-2364.