J Mater Sci: Mater Electron (2017) 28:8130–8135
DOI 10.1007/s10854-017-6519-0

An experimental study of magnetorheological fluids on electrical conductivity property

Xiongbo Yang[1] · **Yuehua Huang**[2] · **Yaqian Hou**[1] · **Hao Wu**[1] · **Ruizhen Xu**[1,3] ·
Paul K. Chu[3]

Received: 22 December 2016 / Accepted: 30 January 2017 / Published online: 11 February 2017

Abstract Magnetorheological fluids (MRFs) are smart materials made by base fluid, magnetizable particles, and stabilizer additives. A series of samples on varying of silicone oil, carbonyl iron particles, and oleic acid were prepared to investigate the stability of sedimentation and electrical conductivity property. Experimental results showed that the sample with mole ratio of oleic acid and carbonyl iron particles is two has the smallest saturation resistance, fastest response to external field, and the best stability of sedimentation. Further investigations suggested that low silicone oil viscosity and suitable amount carbonyl iron particles were desirable for enhance the electrical conductivity property of MRFs.

1 Introduction

Magnetorheological fluids (MRFs) are known as the smart materials, which contains magnetic mirco-particles dispersing in a liquid phase media with surfactants [1–5]. The properties can be controlled with the help of metallic particles and magnetic field [3]. A remarkable property is that its fluidity can be modified from the intensity of an external magnetic field [6]. Under a magnetic field, magnetic particles orientate along the magnetic field lines, and form a chain structure which increases the fluid viscosity. In a result, MRFs can convert from liquid state to semi-solid state. This phenomenon is called magnetoreheological effect (MR effect). For their excellent MR effect, MRFs are widely used in various applications of brakes, dampers, clutches and shock absorbers systems [7, 8].

Except the controllable mechanical properties of MRFs, another important electrical property has been discovered in recent decades. Bica et al. found that the resistance value of MRFs was reduced in the presence of an external magnetic field [9–12]. In the research of our group, we found the value of resistance could vary from infinite to below 200 Ω when applying an external magnetic field [13]. The results indicated that this MRFs had the property of magnetic-field-tuned insulator to conductor transition.

The electrical conductivity of MRFs was affected by many conditions [14–19]. The MRFs usually has three main constituents: base fluid, magnetizable particles, and stabilizer additives. The major issue is the type and fraction of ingredients [3]. Many literatures reported that the characteristics of MRFs were influenced by these three main constituents [20, 21]. The stabilizer additives are utilized to improve the sedimentation of the heavy magnetizable particles. The long carbon chain of fatty acid will increase the dispersion of magnetizable particles and improve the stability of MRFs [22]. Ashtiani et al. studied the effect of fatty acid chain length on the stabilization and rheological properties and the stearic acid with 18 carbon atoms shows best stability and MR effect [23]. The base fluid acts like a carrier which suspending metallic particles inside. Silicone oil, as a common base fluid, its viscosity will affect the property of MRFs. Liu

---

✉ Ruizhen Xu
angiehust2002@hotmail.com

✉ Paul K. Chu
paul.chu@cityu.edu.hk

[1] College of Science, China Three Gorges University, Yichang 443002, China

[2] College of Electrical Engineering and New Energy, China Three Gorges University, Yichang 443002, China

[3] Department of Physics and Materials Science, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong, China

et al. found that the silicone oil viscosity has a significant influence on sedimentation stability, but little impact on shear yield stress [21]. The magnetizable particles play key role in magnetorheological effect [3]. The property of MRFs will influence by many factors, like the size of particle, and the coated materials. Zhang et al. investigated the effect of particle size on the wear property of MRFs [20]. Our group has synthesized a better conductivity of MRFs by coated silver on carbonyl iron [24].

In this work, three main constituents were selected from commonly used materials, which is the silicone oil, carbonyl iron mircoparticles, and oleic acid. MRFs was prepared by dispersed carbonyl iron particles in silicone oil and adding oleic acid as surfactant. The electrical conductivity property of MRFs was measured under different ratio of oleic acid and carbonyl iron particles, with different viscosity of silicone oil, and different amount of carbonyl iron particles.

Table 1 Parameters of the MRFs samples

Sample	Mole ratio of oleic acid and carbonyl iron particlesα	Viscosity of silicone oil β (cs)	Mass of carbonyl iron particles γ (g)
A1	0.5	200	3
A2	1		
A3	2		
A4	5		
A5	8		
B1	2	200	3
B2		350	
B3		500	
C1	2	200	0.5
C2			1
C3			2
C4			4
C5			5
C6			6

2 Experiments

2.1 Sample preparation

Spherical carbonyl iron micro-particles (particle size 1–4 μm, purity >99%, Badische Anilin-und-Soda-Fabrik, Germany) were used as the magnetizable particles without further treatment. The base fluid was silicone oil (Jiaxing Green silicone Co. Ltd), and the stabilizer additive employed was oleic acid (Sigma–Aldrich).

Three constituents, oleic acid, carbonyl iron, and silicone oil, were introduced in a flask to synthesize MRFs. Each mixture was stirred at around 100 rpm and heated at 70 °C for 30 min until a homogeneous solution was obtained.

2.2 Experimental design

The electrical conductivity property of MRFs maybe influent by the ratio of oleic acid and carbonyl iron, the viscosity of silicone oil, and the quantity of carbonyl iron. To study the electrical conductivity property of MRSs, three comparable-group tests were designed, as shown in Table 1. α represents the mole ratio of oleic acid and carbonyl iron particles, β is on behalf of the viscosity of silicone oil, and γ is the mass of carbonyl iron particles. A, B, and C were indicating three groups of tests. The resistance of the MRFs was measured with a special design instrument described previously [24, 25].

3 Results and discussion

3.1 Characterization of magnetic particles

Carbonyl iron microparticles, a widely used material in MRFs synthesis, have high magnetization property [6]. The morphology and grain size of carbonyl iron particles were explored using a scanning electron microscope (SEM). Figure 1a displays the particle has a spherical morphology and the particle size distribution around 1–4 μm. The magnetorheological behavior of carbonyl iron particles was measured by a vibrating sample magnetometer (VSM). As shown in Fig. 1b, the magnetization curve reveals a high magnetic saturation. When the applied magnetic field is 8 kOe, the magnetic saturation reaches to about 190 emu/g. The inset figure in Fig. 1b depicts the magnetic hysteresis loop is hardly to be detected. The high saturation magnetization and low magnetic coercivity characteristics illustrate that the carbonyl iron particles are easily magnetized and demagnetized, which is possible to control reversibly rheological property of MRFs [1, 26].

3.2 Stability tests

One of the challenges in MRFs technology is the stability against sedimentation. Due to the gravity and density mismatch between magnetic particles and carrier fluid, sedimentation occur and restrict widespread applications of MRFs [27]. Sedimentation of the particles operation of the device can be unstable and cause some errors. Viscosity of the base fluid is an important issue in stability of MRFs. Although the low viscosity can lead to instability and sedimentation

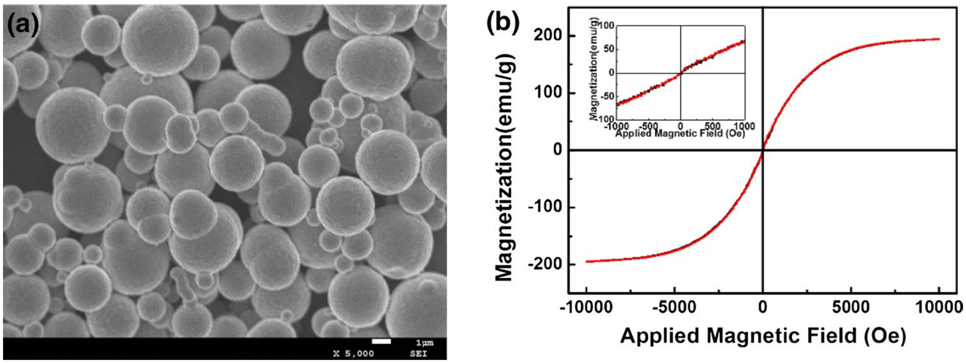

Fig. 1 **a** SEM image of the carbonyl iron particles and **b** its magnetization curve

problems, a high viscosity may raise viscosity of the MRFs in the absence of a magnetic field which is undesirable [28, 29]. Therefore, low viscosity oil, like silicone oil, is preferred to prepare MRFs [3]. Another ingredient for synthesis MRFs is stabilizer additive, which is utilized to overcome sedimentation problem of heavy metallic particles. Bica et al. investigated the effect of different surfactants on the stability of a water-based MRFs [30]. However, the ratio of surfactant and magnetic particles may also influent the sedimentation problem of MRFs. Sample A, listing on Table 1, was prepared to measure the sedimentation rate of MRFs.

In this test, the silicone oil with 200 cs viscosity was selected, and the quantity of carbonyl iron particles was 3 g in every sample. Five samples were prepared by varying the mole ratio of oleic acid and carbonyl iron particles. Caused by the heavy carbonyl iron particles, the prepared MRFs tends to form a transparent layer (continuous phase) on the top by settle stationary. Stability tests were measured by detecting the interface between two phases. Each sample was placed into a cylindrical glass test tube, h_1 is the total height of the MRFs and h_2 is the height of supernatant liquid at specific intervals (Fig. 2a). The sedimentation rate (S_r) is defined as the following equation.

$$S_r\,(\%) = \frac{h_2}{h_1} \times 100\% \tag{1}$$

The smaller S_r indicates slower sedimentation rate and more stable property of MRFs.

Figure 2b depicts sedimentation rate of samples containing different ratio of α. During the measurement, the S_r of A4 and A5 samples are increased quickly and reach to 46 and 24% respectively after 1 h and stable at 47 and 94% respectively. The increase of S_r indicating a fast sedimentation rate. Sample A1, A2, and A3 with smaller ratio of α show better stability, and the sedimentation rates are nearly 2% after 8 h. The S_r of A1 and A2 stable at 5 and 4% respectively. The S_r of A3 sample is 3% after 20 h stewing. It is obvious that samples with more weight fraction of magnetic particles, like α is 5 and 8, lead to undesirable increase in S_r. In addition, the smallest α sample A1 is not the lowest S_r which indicating that excessive media results in formation of superstratum layer. The lowest sedimentation rate sample A3, with mole ratio of oleic acid and carbonyl iron particles is 2, has suitable amount of media to trap heavy dispersed particles and restricts their precipitation.

3.3 Electrical conductivity analysis

The electrical conductivity characteristics were examined using a source meter collaborated with a magneto–resistor device, which generates a homogeneous magnetic field perpendicular to the fluid flow direction.

The curves in Fig. 3a are the electrical conductivities of different sample A response expressing as resistance R versus magnetic field intensity H. Without applying magnetic

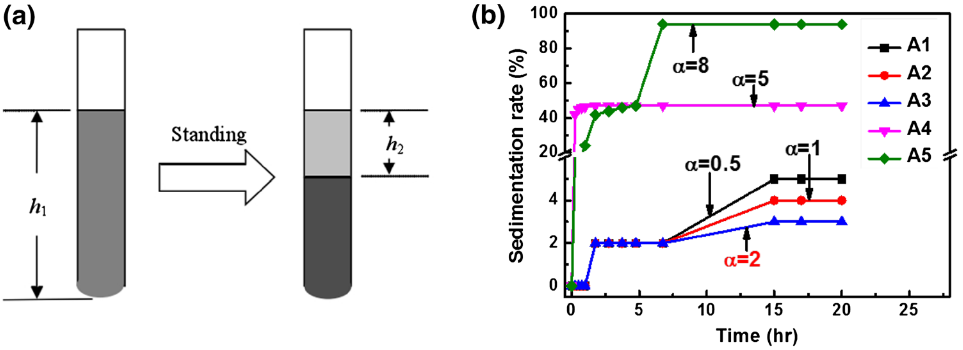

Fig. 2 **a** Schematic diagram of sedimentation ratio and **b** stability measurement curves for different ratio of α

field, the resistivity of the MRFs is too high to detect by the source meter. When applied an external magnetic field, different samples have similar responses. The resistances of every sample A dropped sharply at initial period, and the high value of resistance suggesting few contact between carbonyl iron particles because of poorly organized in the fluids. When H is increased, the particles rearranged, filled the empty space, and formed chains. The increased contact surface between particles result in decreased resistance. The resistances of all sample A stabilized at a low value, which is defined as saturation R (R_s). From high resistance to saturation resistance, there is an inflection point on the curve, which is the particles responses to the H and defined as changing H (H_c). When the mole ratio of oleic acid and carbonyl iron particles α increased, the R_s and H_c both are decreased firstly and increased again. The minimum values of R_s and H_c are 2.4 KΩ and 167 mT respectively, which is belong to sample A3 (Table 2). The A3 sample, with mole ratio of oleic acid and carbonyl iron particles α is 2, not only has the smallest resistance and fastest response to external field, but also has the best stability of sedimentation. Therefore parameter α of A3 was chosen for the rest of experiments.

In order to get a better understanding of the influence of base fluid viscosity on the electrical conductivity property of MRFs, different viscous silicone oils were employed to investigate. The corresponding silicone oil viscosity of B1, B2 and B3 are 200, 350 and 500 cs. The response curves of three samples are similar as shown in Fig. 4a. The R_s and H_c rising when increasing the viscosity. The smallest R_s and H_c sample is B1, which has lowest viscosity (Table 2). The motion of rearrangement of particles were hampered by high oil viscosity. Low viscosity is desirable for better electrical conductivity of MRFs.

The effect of the quantity of carbonyl iron particles on the electrical conductivity property of MRFs was studied. As displayed on Fig. 5a, the quantity of particle is a key role to the R_s and H_c. With the increasing of particle mass from 0.5 to 6 g, H_c decreased from 403 to 128 mT (for 4 g), and then increased to 246 mT. R_s has the same tendency with H_c and the lowest R_s is 1.9 KΩ from sample C4. Even though all samples have same mass fraction of oleic acid and particle, samples with different amount of particles showed different electrical conductivity property. If no magnetic field is applied, the ferromagnetic particles are freely dispersed uniformly in carrier fluids. Under the force of the magnetic field, the particles are polarized and the adjacent particles will close up to form chains, which result in the decrease of resistance. When the quantity of particles increased, there is more chains to form. It is noteworthy that the aggregating of the scattered chains into a column will not change the sample's resistance, the sample's conductivity is mainly contributed by the complete chains [12]. Moreover, the percentage of the particles of

Table 2 Electrical conductivity parameters of different MRFs samples

Sample	Changing H (mT)	Saturation R (KΩ)
A1	324	120
A2	284	18
A3	167	2.4
A4	324	23
A5	402	30
B1	167	2.4
B2	207	28
B3	246	67
C1	403	250
C2	246	25
C3	167	13
C4	128	1.9
C5	167	14
C6	246	42

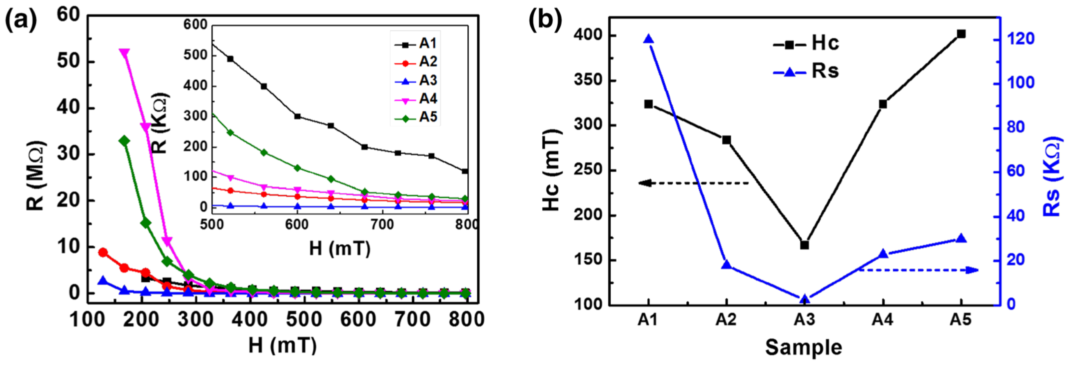

Fig. 3 **a** The electrical conductivity of different sample A under an applied magnetic field H. The *inset* figure is amplification in lower resistances. **b** Changing magnetic field intensity H_c and saturation resistance R_s of different sample A

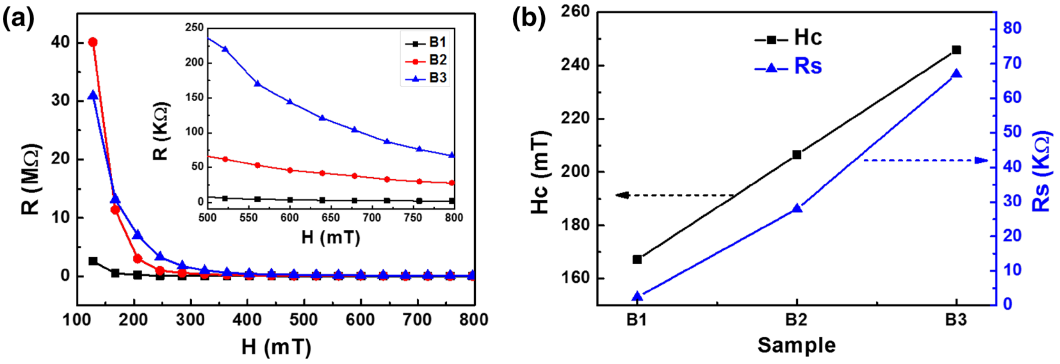

Fig. 4 **a** The electrical conductivity of different sample B under an applied magnetic field H. The *inset* figure is amplification in lower resistances. **b** Changing magnetic field intensity H_c and saturation resistance R_s of different sample B

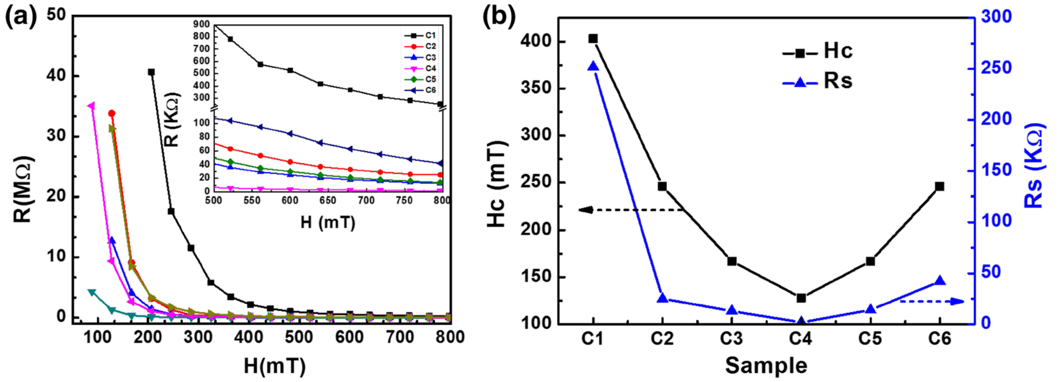

Fig. 5 **a** The electrical conductivity of different sample C under an applied magnetic field H. The *inset* figure is amplification in lower resistances. **b** Changing magnetic field intensity H_c and saturation resistance R_s of different sample C

the complete chains is decided by the intrinsic properties of the sample, including the particles' density, the moment of the particles, and the inevitable local inhomogeneous distribution of the particles [31]. When the superfluous particles present, some incomplete chains and isolated cluster are coexisting, which undermine the formation of complete chains. Not only the fraction of surfactant and particle, but also the amount of particle will influent H_c and R_s of the sample.

4 Conclusions

MRFs based on carbonyl iron microparticles dispersed in silicone oil with oleic acid are prepared. The stability of sedimentation and electrical conductivity property were greatly influenced by the ratio of particles and oleic acid α. It was observed that adding particles to oleic acid up to mole ratio 2 decreased H_c and R_s and improved stability behavior. Higher fractions α did not result in desirable stability and conductivity. Furthermore, sample with low viscosity silicone oil and suitable amount carbonyl iron particles was easier to form complete chains, which result in improving the electrical conductivity property of MRFs.

Acknowledgements The work was financially supported by China Three Gorges University Talent Start-up Funds Nos. KJ2014B079 and KJ2014B080, Scientific Research Project of Yichang City No. A16-302-a14, as well as Hong Kong Research Grants Council (RGC) General Research Funds (GRF) No. CityU 11301215.

References

1. A. Ghaffari, S.H. Hashemabadi, M. Ashtiani, A review on the simulation and modeling of magnetorheological fluids. J. Intel. Mater. Syst. Struct. **26**, 881–904 (2015)
2. X.P. Do, S.B. Choi, High loaded mounts for vibration control using magnetorheological fluids: review of design configuration. Shock Vib. (2015). Doi:10.1155/2015/915859
3. M. Ashtiani, S.H. Hashemabadi, A. Ghaffari, A review on the magnetorheological fluid preparation and stabilization. J. Magn. Magn. Mater. **374**, 716–730 (2015)
4. A.Y. Abd Fatah, S.A. Mazlan, T. Koga, H. Zamzuri, M. Zeinali, F. Imaduddin, A review of design and modeling of

magnetorheological valve. Int. J. Mod. Phys. B **29**, 1530004 (2015)

5. J. de Vicente, D.J. Klingenberg, R. Hidalgo-Alvarez, Magnetorheological fluids: a review. Soft Matter **7**, 3701–3710 (2011)
6. S. Genc, P.P. Phule, Rheological properties of magnetorheological fluids. Smart Mater. Struct. **11**, 140–146 (2002)
7. X.K. Wei, M. Zhu, L.M. Jia, A semi-active control suspension system for railway vehicles with magnetorheological fluid dampers. Vehicle Syst. Dyn. **54**, 982–1003 (2016)
8. D. Case, B. Taheri, E. Richer, Dynamical modeling and experimental study of a small-scale magnetorheological damper. IEEE Asme Trans. Mechatron. **19**, 1015–1024 (2014)
9. I. Bica, Electroconductive magnetorheological suspensions. Smart Mater. Struct. **15**, N151 (2006)
10. I. Bica, Electrical conductivity of magnetorheological suspensions based on iron microparticles and mineral oil in alternative magnetic field. J. Ind. Eng. Chem. **12**, 806–810 (2006)
11. I. Bica, The influence of temperature and of a longitudinal magnetic field upon the electrical conductivity of magnetorheological suspensions. Physica B **371**, 145–148 (2006)
12. J. Vezys, E. Dragasius, V. Volkovas, A. Mystkowski, E. Korobko, The sedimentation of magneto-rheological fluid monitoring system based on resistivity measuring. Mechanika **22**, 449–452 (2016)
13. Y.H. Huang, Y.H. Jiang, X.B. Yang, R.Z. Xu, Influence of oleic and lauric acid on the stability of magnetorheological fluids. J. Magn. **20**, 317–321 (2015)
14. I. Bica, Giant resistances based on magnetorheological suspensions. J. Ind. Eng. Chem. **13**, 299–304 (2007)
15. I. Bica, The influence of hydrostatic pressure and transverse magnetic field on the electric conductivity of the magnetorheological elastomers. J. Ind. Eng. Chem. **18**, 483–486 (2012)
16. I. Bica, E.M. Anitas, L.M.E. Averis, Influence of magnetic field on dispersion and dissipation of electric field of low and medium frequencies in hybrid magnetorheological suspensions. J. Ind. Eng. Chem. **27**, 334–340 (2015)
17. I. Bica, E.M. Anitas, M. Bunoiu, B. Vatzulik, I. Juganaru, Hybrid magnetorheological elastomer: influence of magnetic field and compression pressure on its electrical conductivity. J. Ind. Eng. Chem. **20**, 3994–3999 (2014)
18. I. Bica, M. Balasoiu, M. Bunoiu, L. Iordaconiu, Microparticles and electroconductive magnetorheological suspensions. Rom. J. Phys. **61**, 926–945 (2016)
19. L. Bica, Magnetorheological suspension based on mineral oil, iron and graphite micro-particles. J. Magn. Magn. Mater. **283**, 335–343 (2004)
20. Q.X. Zhang, X.H. Liu, Y.K. Ren, L.F. Wang, Y. Hu, Effect of particle size on the wear property of magnetorheological fluid. Adv. Mater. Sci. Eng. (2016). Doi:10.1155/2016/4740986
21. X.H. Liu, L.F. Wang, H. Lu, D.D. Wang, Q.Q. Chen, Z.B. Wang, Effect of silicone oil viscosity on the properties of magnetorheological fluids. Optoelectron. Adv. Mater. **9**, 226–230 (2015)
22. M.R. Morrow, J.P. Whitehead, D. Lu, Chain-length dependence of lipid bilayer properties near the liquid-crystal to gel phase-transition. Biophys. J. **63**, 18–27 (1992)
23. M. Ashtiani, S.H. Hashemabadi, An experimental study on the effect of fatty acid chain length on the magnetorheological fluid stabilization and rheological properties. Colloid Surf. A **469**, 29–35 (2015)
24. Y.H. Huang, Y.H. Jiang, X.B. Yang, H.Y. Sun, H.G. Piao, R.Z. Xu, Enhanced conductivity of magnetorheological fluids based on silver coated carbonyl particles. J. Mater. Sci. Mater. Electron. **27**, 255–259 (2016)
25. X.B. Yang, Y.H. Jiang, Y.H. Huang, R.Z. Xu, H.G. Piao, G.M. Jia, X.Y. Tan, Magnetic-field-tuned insulator to conductor transition in magnetorheological suspension. J. Magn. **19**, 345–348 (2014)
26. H.J. Choi, I.B. Jang, J.Y. Lee, A. Pich, S. Bhattacharya, H.J. Adler, Magnetorheology of synthesized core-shell structured nanoparticle. IEEE Trans. Magn. **41**, 3448–3450 (2005)
27. N.M. Wereley, A. Chaudhuri, J.H. Yoo, S. John, S. Kotha, A. Suggs, R. Radhakrishnan, B.J. Love, T.S. Sudarshan, Bidisperse magnetorheological fluids using Fe particles at nanometer and micron scale. J. Intel. Mater. Syst. Struct. **17**, 393–401 (2006)
28. W.Q. Jiang, Y.L. Zhang, S.H. Xuan, C.Y. Guo, X.L. Gong, Dimorphic magnetorheological fluid with improved rheological properties. J. Magn. Magn. Mater. **323**, 3246–3250 (2011)
29. F.F. Fang, J.H. Kim, H.J. Choi, Synthesis of core-shell structured PS/Fe3O4 microbeads and their magnetorheology. Polymer **50**, 2290–2293 (2009)
30. D. Bica, L. Vekas, M.V. Avdeev, O. Marinica, V. Socoliuc, M. Balasoiu, V.M. Garamus, Sterically stabilized water based magnetic fluids: synthesis, structure and properties. J. Magn. Magn. Mater. **311**, 17–21 (2007)
31. X. Chen, X.Q. Zhu, Z.Y. Xu, Y.C. Lin, G.T. He, The research of the conductive mechanism and properties of magnetorheological fluids. Physica B **418**, 32–35 (2013)