

Influence of surfactants on shear-thickening behavior in concentrated polymer dispersions

Fang Ye · Wei Zhu · Wanquan Jiang ·
Zhiyuan Wang · Qian Chen · Xinglong Gong ·
Shouhu Xuan

Received: 1 July 2013 / Accepted: 10 November 2013
© Springer Science+Business Media Dordrecht 2013

Abstract Concentrated dispersions consisting of 310 nm poly(styrene–ethylacrylate) nanospheres and ethylene glycol, which exhibited pronounced shear-thickening behavior, were prepared in this work. The influence of surfactants on their shear-thickening behavior was investigated, which indicated that the surfactants affected the shear-thickening behavior by changing the surface force and interparticle force. Various surfactants, such as cationic, anionic, non-ionic, and zwitterionic surfactants were added to the shear-thickening fluid (STF) and their rheological properties were measured. The results indicated that all kinds of surfactants could enhance shear-thickening behavior by changing their electrostatic, steric, or lubrication interaction, especially for nonionic surfactant Triton X-100 (TX100) and cationic surfactant

cetyltrimethyl ammonium bromide (CTAB). TX100 led to the maximum viscosity up to 1,650 Pa s and CTAB enhanced the maximum viscosity up to 1,000 Pa s when the introduced surfactants were only 2 and 0.3 %, both values were nearly five times larger than the neat STFs. A plausible explanation for the enhancing mechanism by different kinds of surfactants was discussed.

Keywords Shear-thickening · Surfactant · Styrene–ethylacrylate copolymer · Viscosity

Introduction

Shear-thickening (ST) is a nonlinear flow behavior marked by a shear viscosity increase with increasing applied shear rate or shear stress, which is general exist in concentrated dispersions (Barnes 1989). Beyond a critical shear rate, the viscosity may increase by orders of magnitude. This behavior is also reversible, which means the viscosity immediately decreases to initial state when the shear stress is removed. With the ST behavior, shear-thickening fluid (STF) has attracted considerable interests in the design of human body armor, dampers or impact absorbers, control devices, and probe of the nanoscale forces operational, etc. (Zhang et al. 2008; Wereley 2008; Fischer et al. 2006; Wagner and Bender 2004; Lee et al. 2003; Helber et al. 1990).

It is believed that ST in stable concentrated suspensions arises from formation of particle clusters

Electronic supplementary material The online version of this article (doi:10.1007/s11051-013-2122-3) contains supplementary material, which is available to authorized users.

F. Ye · W. Zhu · W. Jiang (✉)
Department of Chemistry, Collaborative Innovation
Center of Suzhou Nano Science and Technology,
University of Science and Technology of China (USTC),
Hefei 230026, People's Republic of China
e-mail: jiangwq@ustc.edu.cn

Z. Wang · Q. Chen · X. Gong (✉) · S. Xuan
CAS Key Laboratory of Mechanical Behavior and Design
of Materials, Department of Modern Mechanics, USTC,
Hefei 230027, People's Republic of China
e-mail: gongxl@ustc.edu.cn

induced by the dominance of short-range lubrication hydrodynamic interactions. Brady and Bossis (1985) first predicted the flow-induced particle density fluctuations, denoted as “hydroclusters” by Stokesian dynamics simulations. Then experimental evidences for hydroclusters were provided by subsequent researchers with rheo-optical and neutron scattering methods. Kalman and Wagner (2009) developed and demonstrated a method of flow-ultra small angle neutron scattering to probe the colloidal microstructure and characterize the formation of hydroclusters. Their observations provided direct evidence for the formation of hydroclusters in stable, near hard-sphere colloidal suspensions. They also demonstrated that an order–disorder transition may accompany ST, but was not necessary for the happening of ST. Recently, by combining fast confocal microscopy with simultaneous force measurements, Cheng et al. (2011) pointed out that the ST arose from particle clustering induced by hydrodynamic lubrication forces.

The rheological properties of STF are influenced by various factors, such as the characteristics of dispersed particles (including the maximum packing fraction, type, shape, size, polydispersion, and interparticle action) and the solvents (Yu et al. 2012; Maranzano and Wagner 2001; Maranzano and Wagner 2002; Lee et al. 1999; Brown et al. 2010; Chang et al. 2011; Shenoy and Wagner 2005; Jiang et al. 2010). Besides these parameters of the system itself, additives also exhibited great effect on ST behavior. Many groups have conducted intensive studies on ST behavior by adding the additives to the system. Franks et al. (2000) reported the effect of interparticle forces on ST of oxide dispersions after introducing acid (HCl, HNO₃), base (KOH, NaOH), and salt (KNO₃) to change the range and magnitude of the repulsive forces. Yang et al. (2001) studied the PH dependent rheological behaviors of titanium dioxide suspensions by adding HNO₃ or NaOH to alter particle surface charge. In addition, Xu et al. (2010) investigated the influence of additives with different molecular chain lengths on ST of dispersion and concluded that as the molecular weight increased, the molecular chain increased; and thus a larger network structure would be formed between the particles and the dispersion medium leading to an enhanced ST effect. Kamibayashi et al. (2008) researched the effect of the molecular weight and concentration of poly(ethylene oxide) on the viscosity behavior for suspensions of silica in polymer

solutions, and they found that the shear-induced formation of transient network was responsible for the ST flow for nanoparticle suspensions flocculated by polymer bridging. The surface properties of particles would be modified due to the addition of additive. The change in the interaction of particle–particle and particle-dispersing medium might follow. Thus, the rheological properties changed, and we can explore the influences of these interaction forces on ST of suspensions in turn. Moreover, unique structure of additive itself would promote the formation of clusters which improved the ST effect of STF. With the development of STF various properties of STF were required. The rheological properties of STF can be easily altered via mixing with different additives. Therefore, it is significant to study the effects of various additives on the ST behavior of the STF.

The surfactant is a kind of amphiphilic molecule, which can modify the particle’s surface chemistry; thus, they can be used as additives to improve the ST effects of STF. To achieve a better understanding of the ST behavior, the systematic investigation of the surfactants influence on the ST in concentrated dispersion is authentically necessary. In this work, concentrated dispersions consisting of poly(styrene–ethylacrylate) copolymer (PSt–EA) particles and ethylene glycol were prepared and they exhibited pronounced ST effect. We systematically investigated the influence of surfactants kinds on ST behavior in concentrated dispersions. Diverse surfactants, such as cationic, anionic, nonionic, and zwitterionic surfactants were added to STFs and the rheological properties of obtained STFs were measured. Both steady shear and oscillatory shear tests were conducted on each sample. A plausible explanation for mechanism of enhancement of ST by different kinds of surfactants was also discussed.

Experimental methods

Materials

Ethylacrylate (EA), acrylic acid (AA), ethylene glycol (EG), potassium peroxydisulfate (K₂S₂O₈), sodium dodecylbenzene sulfonate (DBS), bis(2-ethylhexyl) sulfosuccinate (AOT), sodium dodecyl sulfate (SDS), Triton X-100 (TX100), cetyltrimethyl ammonium bromide (CTAB), 3-(*N,N*-dimethylmyristylammonio)propanesulfonate (DAPS) were used as received. Styrene

(St) was distilled under vacuum before being used. All the reagents were purchased from Sinopharm Chemical Reagent Co., Ltd. Twice-distilled water was used in the present study.

The preparation of PSt–EA particles

The polymerization was conducted in a 500 mL three-necked flask, which was fitted with a mechanical stirrer, a reflux condenser, and a nitrogen inlet. St, EA, AA, and distilled water were firstly added to the flask and stirred for 30 min at room temperature. Then $K_2S_2O_8$ was introduced as initiator. After 10 min, the reactor was heated up to 75 °C in a water bath and maintained for 6 h. The polymerization was conducted under nitrogen atmosphere and the resultants were collected by centrifugation after the polymerization. The PSt–EA product was rinsed by distilled water for three times and then dried in a vacuum oven at 50 °C.

The preparation of STFs

Typically, the STFs were prepared by dispersing the PSt–EA particles into EG. Then mixtures were milled for 24 h in a ball crusher in order to obtain a uniform distribution of PSt–EA particles within the dispersions and to insure the particles were not aggregated. Before testing, the samples were sonicated for an hour for the purpose of removing the air bubbles. Surfactants were added to STFs in the mixing progress.

Rheological measurements

Rheological properties were measured using a rheometer (Physica, MCR 301, Anton Paar) with a cone plate

having a cone angle of 0.2° and a diameter of 25 mm at temperature 25 °C. Both steady shear and oscillatory shear tests were conducted on each sample. Angular frequency sweep experiments were employed to determine the dynamic ST behaviors, which was performed in rheometer with a gap size of 0.05 mm. For the steady-shear experiment to remove loading effects, a pre-shear of 1 s^{-1} was applied for 60 s prior to further measurement.

Results and discussion

The as-synthesized PSt–EA particles were characterized by scanning electron microscope (SEM, Sirion 200). As shown in Fig. 1, it clearly revealed that the products were monodisperse spheres with uniform size. The average particle diameter was about 310 nm. By dispersing these microspheres into ethylene glycol, stable STF can be obtained. The as-prepared STFs exhibited remarkable ST behavior. Meanwhile, solid volume fraction had great effect on ST. ST became severer with increased volume fraction, which was shown as lower critical shear rate and higher viscosity (see Fig. S1 Supporting Information).

In order to investigate influence of the surfactants on the ST behavior, diverse surfactants were added to STFs and their rheological properties were investigated, respectively. The obtained samples were denoted as STF-surfactant (mass fraction). For example, STF–SDS (2 %) meant that 2 wt% SDS was added to the STF sample. Since the amount of particles prepared in one reaction was limited, the particles used in a set of the experiments were synthesized in one time but were not produced by one time used in different groups of experiments. Therefore, the

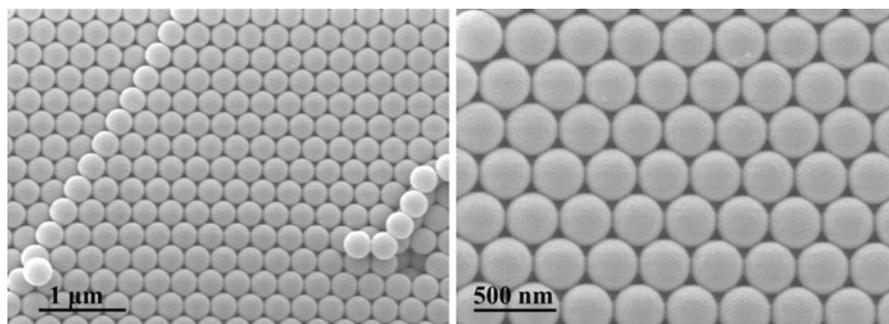


Fig. 1 SEM images of obtained PSt–EA copolymer particles

rheological properties of STF (without any surfactants) display a certain extent of differences.

Effect of surfactants type

The influence of surfactants on ST in concentrated dispersions was systematically investigated. Rheological properties of STF with different surfactants, such as cationic, anionic, nonionic, and zwitterionic surfactants, were measured. Both the anionic and non-ionic surfactants can improve the ST effect of STF. Figure 2 shows steady shear sweep plots for STF with different surfactants. The volume fraction of PS₂-EA particles was 67 % and the added surfactants were 2 % (relative to the weight of STF sample). As shown in Fig. 2, with increasing of shear rate, viscosity of each sample first decreased slightly, and then dramatically soared and reached maximum. After that, the viscosity of the STF dropped rapidly, which was a consequence of “jamming” resulted by the severe ST and further solidifying and slipping of the sample. The critical shear rate of the corresponding STF was 92 s^{-1} , and the viscosity dramatically increased up to 284 Pa s beyond this shear rate. When surfactants were introduced to the STF, the critical shear rate ($\dot{\gamma}_c$) decreased and the maximum viscosity (η_{\max}) increased, which indicated an improvement in ST effect. The anionic surfactants we studied included DBS, AOT, and SDS. Figure 2 clearly revealed that $\dot{\gamma}_c$ of STF with anionic surfactants were similar and the values were about 30 s^{-1} . Maximum viscosities of them were between 321 to 390 Pa s. Similar surface

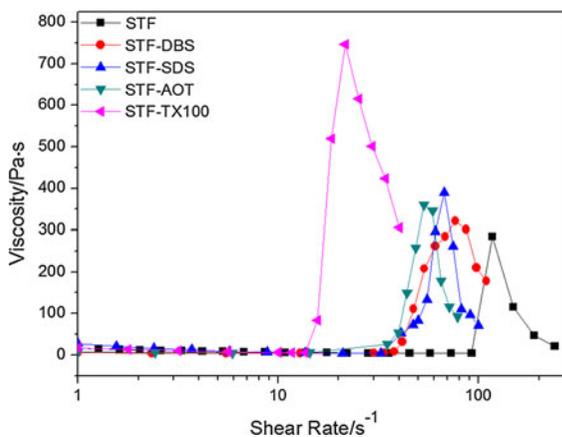


Fig. 2 Viscosity versus shear rate for STF with different surfactants

activities of these three anionic surfactants may account for the similar influences on ST behavior. Furthermore, when nonionic surfactant TX100 was added to STF, $\dot{\gamma}_c$ dramatically decreased to 13.6 s^{-1} and η_{\max} increased to 747 Pa s, which was remarkably higher than that of STF without TX100. It indicated that the critical shear rate and maximum viscosity of STF were highly dependent on surfactant type. However, when cationic surfactant CTAB was added to STF, the STF sample was no longer a suspension but became a near-solid non-fluid state.

Effect of concentration

In order to further explore the particular influence of surfactants on the ST behavior, we systematically investigated the rheological properties of STF with different mass fractions of diverse surfactants. Rheological properties of STF with different mass fractions of SDS were measured under steady shear and oscillatory shear mode. Figure 3a shows viscosity as a function of shear rate for STF with different SDS concentrations. For each sample, with increasing of shear rate, viscosity firstly decreased and then surged when critical shear rate was reached. The shear thinning at lower shear rate arises from transformation from three-dimensional ordered structure to a two-dimensionally layered structure that permits continuous deformation (Lee et al. 1999). As shown in Fig. 3a, $\dot{\gamma}_c$ of STF without SDS was 835 s^{-1} and η_{\max} was 41 Pa s. The maximum viscosities of STF-SDS (0.5 %), STF-SDS (1.0 %), and STF-SDS (2.0 %) were similar and about 106 Pa s. As the amount of SDS increased to 3.0 %, the maximum viscosity was up to 144.2 Pa s. However, the ST effect was weakened with further increasing of the SDS. Resembled to the maximum viscosity, the critical shear rate was also dependent on the mass fraction of SDS. At the beginning, the critical shear rate decreased with increasing the SDS mass fraction; however, it shifted to higher with further increasing. There was an optimal SDS mass fraction for enhancement of ST behavior. In order to observe the changes clearly, plot for critical shear rate and maximum viscosity versus SDS mass fraction are shown in Fig. 3b.

Figure 3c shows complex viscosity versus angular frequency for STF with different amount of SDS. It is known that dynamic ST occurs when an apparent critical strain is reached. STF without SDS and STF

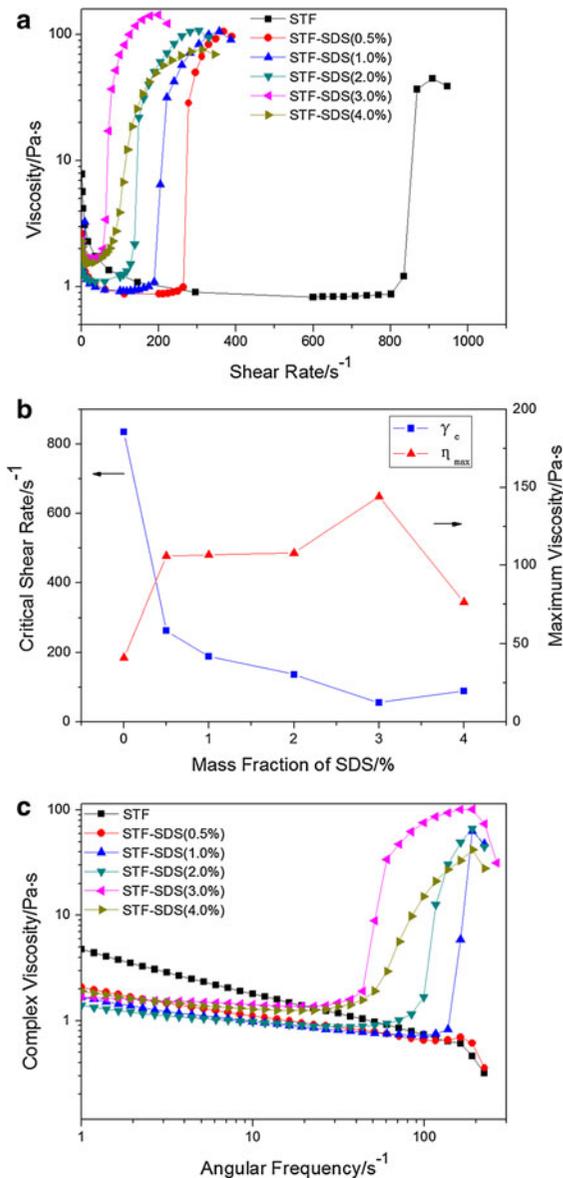


Fig. 3 **a** Viscosity versus shear rate for STFs with different SDS concentration under steady shear mode. **b** Critical shear rate and maximum viscosity versus SDS mass fraction. **c** Complex viscosity versus angular frequency for STFs with different SDS concentration, dynamic frequency sweeps at $T = 25\text{ }^{\circ}\text{C}$, $\gamma = 200\text{ }%$

with 0.5 % SDS was not present ST on the test strain. The trend of oscillatory sweep curves is similar to the steady shear mode. The rheological property of STF–SDS (3 %) was a turning point, which exhibited the lowest critical angular frequency and the severest ST behavior. STFs with different amount of SDS had similar rheological behavior under steady and

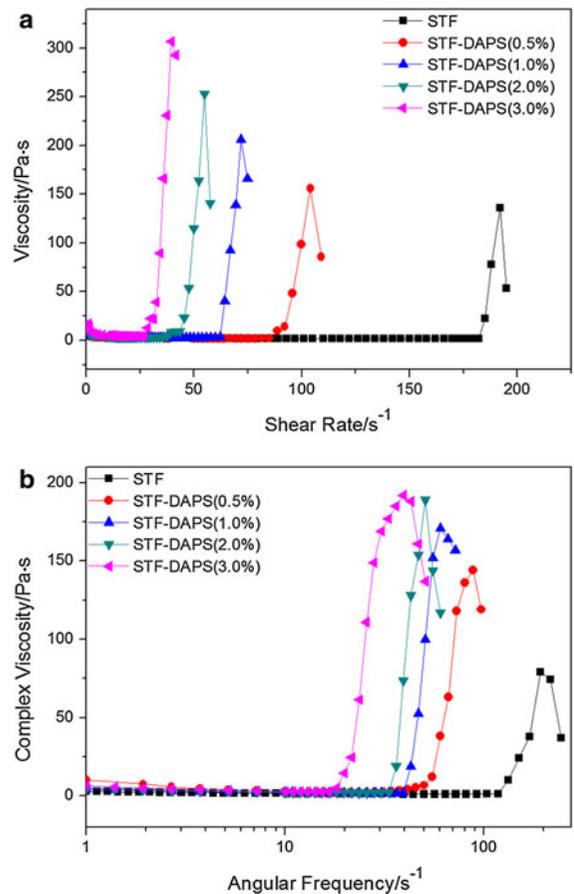


Fig. 4 **a** Viscosity versus shear rate for STFs with different amount of DAPS. **b** Complex viscosity versus angular frequency for STFs with different amount of DAPS, dynamic frequency sweeps at $T = 25\text{ }^{\circ}\text{C}$, $\gamma = 200\text{ }%$

oscillatory shear. All the initial complex viscosities of STFs with SDS were lower than that of the corresponding STF, which may be a consequence of lubrication induced by SDS.

The influence of zwitterionic surfactant on the ST behavior was also investigated. DAPS was chosen as an additive. Figure 4a shows steady shear sweep plot of STFs with different DAPS concentrations. All STFs exhibited typical ST behavior. The critical shear rate was inversely proportional to the SDS mass fraction, whereas the degree of ST was proportional to it. The maximum viscosity of STF–DAPS (3 %) was 307 Pa s, which was nearly 2.3 times larger than that of STF without surfactant. In contrast with that of STF contained SDS, $\dot{\gamma}_c$ and η_{max} of STF with DAPS were changed monotonically and did not exhibit a turning

point. Rheological properties of STF with DAPS under oscillatory shear (shown in Fig. 4b) were resembled to that of steady shear.

We compared critical viscosity (viscosity at the onset of ST) and maximum viscosity for the same DAPS mass fraction and the plot was shown in Fig. 5. A linear fitting algorithm is applied to the data point. The results of fitting showed that the log of maximum viscosity and critical viscosity was linear with DAPS mass fraction. The slope for both maximum viscosity and critical viscosity were 0.118 and 0.114, respectively. Similar slope indicated that the STF had similar microstructure in the onset of ST and ST state.

Nonionic surfactant TX100 could obviously enhance the ST behavior. As shown in Fig. 6a, the critical shear rate of STF in the absence of Triton was 62 s^{-1} and the maximum viscosity was 335 Pa s . With the addition of TX100, the critical shear rate reduced sharply and maximum viscosity increased. Particularly, the maximum viscosity of STF–TX100 (2 %) reached to $1,650 \text{ Pa s}$, which was nearly five times larger than that of STF without Triton. When the amount of Triton was larger than 2 %, STF samples became near-solid and could not be tested. Figure 6b shows complex viscosity curves under oscillatory shear. It indicated that maximum complex viscosity increased with increasing of Triton, which resembled to the trend of viscosity curves under steady shear.

Based on the above results, it was found that when 2 % CTAB was introduced, the STF sample was no longer a suspension but became a near-solid non-fluid state. It can be presumed that CTAB could either

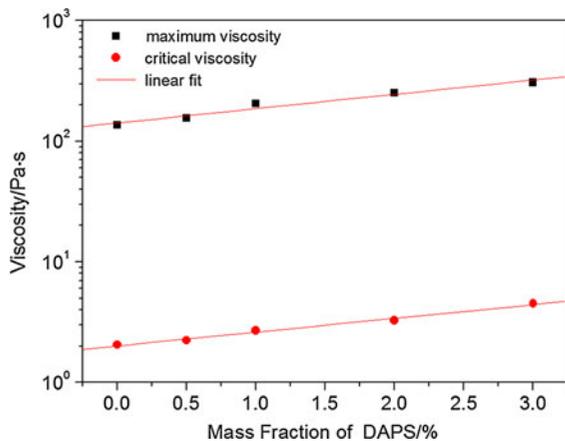


Fig. 5 Critical viscosity and maximum viscosity versus DAPS mass fraction

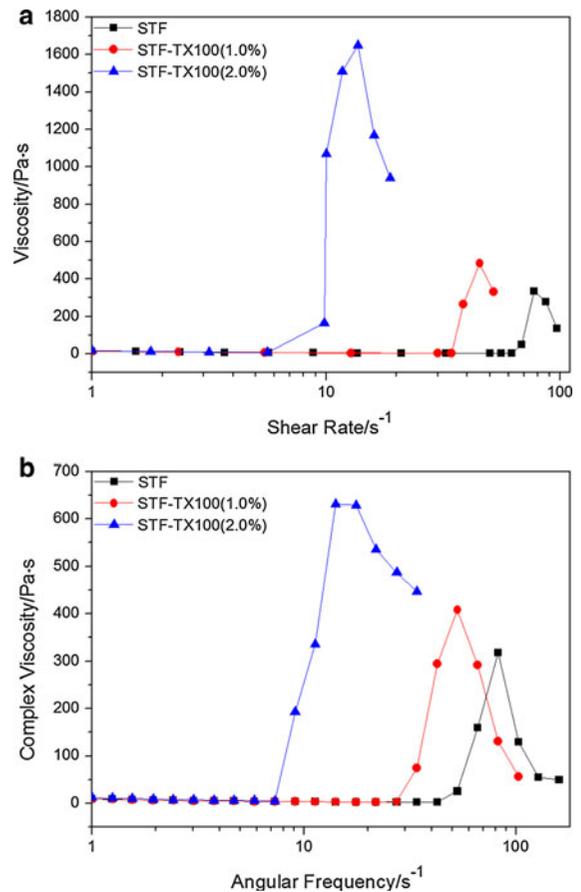


Fig. 6 **a** Viscosity versus shear rate for STFs with different TX100 mass fraction under steady shear mode. **b** Complex viscosity versus angular frequency for STFs with different TX100 mass fraction, dynamic frequency sweeps at $T = 25 \text{ }^\circ\text{C}$, $\gamma = 200 \%$

prevent ST or significantly reinforce ST effect when only very little CTAB was added to the STF. In order to explore the CTAB influence on ST, we studied the rheological properties of STFs with tiny amount of CTAB. As presented in Fig. 7a, ST effect of STF could be greatly improved by CTAB under steady shear mode. The ST behavior was highly dependent on the mass fraction of CTAB. Critical shear rate decreased with increasing CTAB mass fraction, whereas the degree of ST increased. The maximum viscosity of STF–CTAB (0.3 %) was up to $1,000 \text{ Pa s}$, and this value was nearly five times larger than that of the corresponding STF. STF sample became near-solid with further increasing the CTAB. Figure 7b presents the complex viscosity versus angular frequency for STFs with different CTAB mass fraction. It

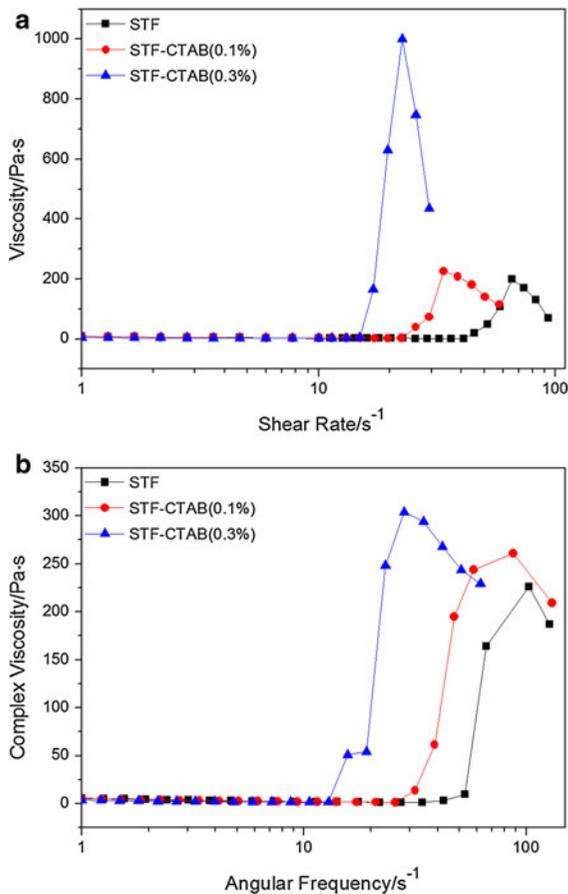


Fig. 7 **a** Viscosity versus shear rate for STFs with different CTAB mass fraction under steady shear mode. **b** Complex viscosity versus angular frequency for STFs with different CTAB mass fraction, dynamic frequency sweeps at $T = 25\text{ }^{\circ}\text{C}$, $\gamma = 200\%$

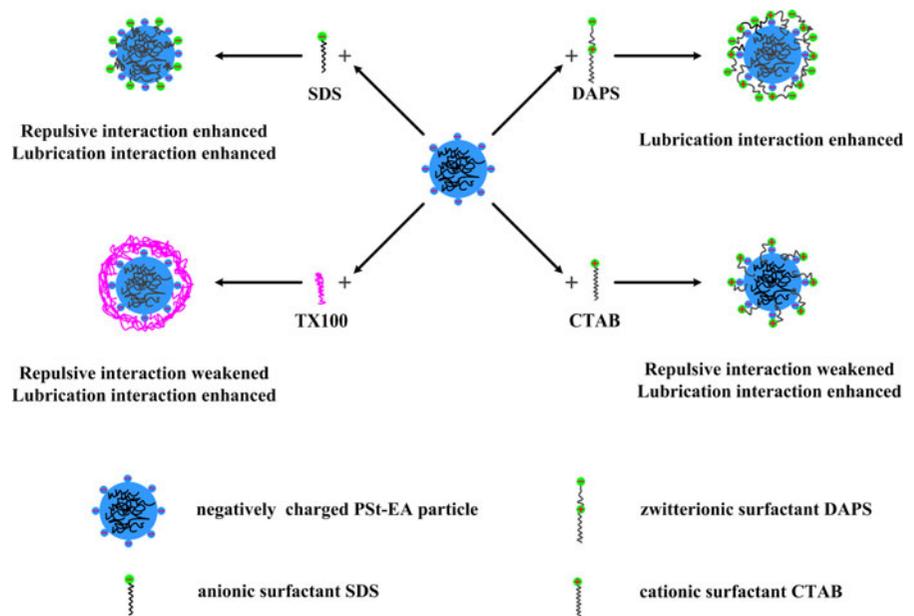
can be seen that the changes of the rheological behavior under steady shear and oscillatory shear are the same, indicating the high credibility.

A plausible influence mechanism

It is believed that ST is a consequence of the formation of hydroclusters due to the dominance of short-ranged lubrication hydrodynamic interactions at relatively high shear rates (Kalman and Wagner 2009). Appropriate surface force, lubrication force, and Brownian motion make suspensions display remarkable ST effect. The PSt-EA particles were synthesized through soap-free emulsion polymerization method. The oligomers of acrylic acid partly served as a kind of surfactant in the reaction. The inside of particles was

hydrophobic group and the surface was partially covered with carboxyl groups; therefore, the particles were negatively charged in dispersion. When anionic surfactant SDS was added to STF, the hydrophobic end attracted with hydrophobic group of PSt-EA particles, and negative charged hydrophilic end was in the surface. Hence, negative charges in PSt-EA particle surface were enhanced, leading to an improvement in electrostatic repulsive interaction of particles. The zeta-potential of PSt-EA particles in aqueous solution was -28.06 mV . When 0.5% SDS was added to the solution, zeta-potential changed to -71.67 mV . It proved SDS indeed enhanced surface negative charge of particles. Meanwhile, the added SDS also reduced hydrophobic interaction between particles and dispersing medium and further intensified lubrication hydrodynamic interaction. It was believed that repulsive interaction led to higher critical shear rate, while lubrication hydrodynamic interaction produced lower critical shear rate and severe ST (Kalman and Wagner 2009; Franks et al. 2000). In our system, it had a competition between these two forces; thus, there was a turning point for rheological property of STFs with different SDS concentration. The $\dot{\gamma}_c$ and η_{\max} of STF-SDS (3%) were minimum and maximum respectively, which indicated severest ST effect. Zwitterionic surfactant DAPS had both the cationic and anionic hydrophilic head. Therefore, it hardly changed the electrostatic interaction among particles of suspension. The influence of DAPS on ST was attributed to the lubrication. Among all the surfactants, both nonionic surfactant TX100 and cationic surfactant CTAB could obviously enhance ST effect. TX100 is a tape of polyoxyethylene surfactant, and the O atom on the oligomer chain can attract with hydroxyl group or carboxyl group of PSt-EA particle surface to form hydrogen bond. Finally, a polymer layer was engendered on the surface of PSt-EA particles. The repulsion interaction among PSt-EA particles was weakened by polymer layer. In addition, lubrication hydrodynamic interaction increased due to the adsorption of TX100. Therefore, particles could approach closer and produced larger hydroclusters at high shear rate, which resulted in severer ST behavior. The hydrophilic end of cationic surfactant CTAB was positively charged. When the suspension was mixed with CTAB, the hydrophilic end of CTAB with positive charge and the COO^- groups in the surface of particles would attract each other due to the

Scheme 1 Influence mechanism of anionic and nonionic surfactants on shear-thickening



electrostatic interaction, which weakened the interparticle repulsion among the particles. Meanwhile, lubrication hydrodynamic interaction was reinforced owing to the adsorption of surfactant CTAB, so dramatic increase was occurred in the severity of ST. The charge on the surface of the particles would be completely neutralized with further adding of CTAB; thus, this system would become unstable and the flocculation happened. The schematic illustration for influence mechanism of various surfactants on ST is shown in Scheme 1.

Conclusion

High performance ST fluids consisting of PS-EA particles and ethylene glycol were prepared. Four kinds of surfactants, containing cationic, anionic, nonionic, and zwitterionic surfactants, were used to investigate the influence of surfactants on ST behavior of STF. Results showed that all four kinds of surfactants can enhance ST behavior, whereas the characteristics of the enhancements were various. Electrostatic repulsive interaction and hydrophilic interaction induced by anion surfactant SDS had conflictive effect on ST. Therefore, there was a turning point of rheological properties for STF with different SDS concentrations. 3 % SDS was optimal for the enhancement of ST. Unlike anion surfactant, the

influence of DAPS on ST was only attributed to the lubrication, so the improvement of ST was monotonic under increasing the amount of DAPS. The adsorption of nonionic surfactant TX100 or cationic surfactant CTAB weakened the interparticle repulsion and reinforced the lubrication hydrodynamic interaction; therefore, both TX100 and CTAB could obviously enhance the ST effect. The investigation of adjusting ST behavior by surfactants might open up new perspectives in preparing stable, efficient, and controllable ST materials and contribute to our understanding of the mechanism of the STF.

Acknowledgments Financial supports from the National Natural Science Foundation of China (Grant Nos. 11372301, 11125210) and the National Basic Research Program of China (973 Program, Grant No. 2012CB937500) are gratefully acknowledged.

References

- Barnes HA (1989) Shear-thickening (“dilatancy”) in suspensions of nonaggregating solid particles dispersed in Newtonian liquids. *J Rheol* 33:329–366
- Brady JF, Bossis G (1985) The rheology of concentrated suspensions of spheres in simple shear flow by numerical simulation. *J Fluid Mech* 155:105–129
- Brown E, Zhang HJ, Forman NA, Maynor BW, Betts DE, DeSimone JM, Jaeger HM (2010) Shear thickening in

- densely packed suspensions of spheres and rods confined to few layers. *J Rheol* 54:1023–1046
- Chang L, Friedrich K, Schlarb AK, Tanner R, Ye L (2011) Shear-thickening behaviour of concentrated polymer dispersions under steady and oscillatory shear. *J Mater Sci* 46:339–346
- Cheng X, McCoy JH, Israelachvili JN, Cohen I (2011) Imaging the microscopic structure of shear thinning and thickening colloidal suspensions. *Science* 333:1276–1279
- Fischer C, Braun SA, Bourban PE, Michaud V, Plummer CJG, Manson JAE (2006) Dynamic properties of sandwich structures with integrated shear-thickening fluids. *Smart Mater Struct* 15:1467–1475
- Franks GV, Zhou ZW, Duin NJ, Boger DV (2000) Effect of interparticle forces on shear thickening of oxide suspensions. *J Rheol* 44:759–779
- Helber R, Doncker F, Bung R (1990) Vibration attenuation by passive stiffness switching mounts. *J Sound Vib* 138:47–57
- Jiang WQ, Sun YQ, Xu YL, Peng C, Gong XL, Zhang Z (2010) Shear-thickening behavior of polymethylmethacrylate particles suspensions in glycerine-water mixtures. *Rheol Acta* 49:1157–1163
- Kalman DP, Wagner NJ (2009) Microstructure of shear-thickening concentrated suspensions determined by flow-USANS. *Rheol Acta* 48:897–908
- Kamibayashi M, Ogura H, Otsubo Y (2008) Shear-thickening flow of nanoparticle suspensions flocculated by polymer bridging. *J Colloid Interface Sci* 321:294–301
- Lee JD, So JH, Yang SM (1999) Rheological behavior and stability of concentrated silica suspensions. *J Rheol* 43:1117–1140
- Lee YS, Wetzel ED, Wagner NJ (2003) The ballistic impact characteristics of Kevlar (R) woven fabrics impregnated with a colloidal shear thickening fluid. *J Mater Sci* 38:2825–2833
- Maranzano BJ, Wagner NJ (2001) The effects of particle size on reversible shear thickening of concentrated colloidal dispersions. *J Chem Phys* 114:10514–10527
- Maranzano BJ, Wagner NJ (2002) Flow-small angle neutron scattering measurements of colloidal dispersion microstructure evolution through the shear thickening transition. *J Chem Phys* 117:10291–10302
- Shenoy SS, Wagner NJ (2005) Influence of medium viscosity and adsorbed polymer on the reversible shear thickening transition in concentrated colloidal dispersions. *Rheol Acta* 44:360–371
- Wagner NJ, Bender JW (2004) The role of nanoscale forces in colloid dispersion rheology. *MRS Bull* 29:100–106
- Wereley NM (2008) Nondimensional herschel–bulkley analysis of magnetorheological and electrorheological dampers. *J Intell Mater Syst Struct* 19:257–268
- Xu YL, Gong XL, Peng C, Sun YQ, Jiang WQ, Zhang Z (2010) Shear thickening fluids based on additives with different concentrations and molecular chain lengths. *Chin J Chem Phys* 23:342–346
- Yang HG, Li CZ, Gu HC, Fang TN (2001) Rheological behavior of titanium dioxide suspensions. *J Colloid Interface Sci* 236:96–103
- Yu KJ, Cao HJ, Qian K, Sha XF, Chen YP (2012) Shear-thickening behavior of modified silica nanoparticles in polyethylene glycol. *J Nanopart Res* 14:747
- Zhang XZ, Li WH, Gong XL (2008) The rheology of shear thickening fluid (STF) and the dynamic performance of an STF-filled damper. *Smart Mater Struct* 17:035027