

Shear thickening behavior of nanoparticle suspensions with carbon nanofillers

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Received: 7 March 2013 / Accepted: 20 June 2013 / Published online: 29 June 2013
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Abstract Suspensions comprised of silica nanoparticle (average diameter: 650 nm) and carbon nanofillers dispersed in polyethylene glycol were prepared and investigated. Rheological measurement demonstrated that the mixed suspensions showed a non-Newtonian flow profile, and the shear thickening effect was enhanced by the addition of carbon nanotubes (CNTs) (main range of diameter: 10–20 nm; length: 5–15 μm ; purity: >97 wt%) and graphene nanoplatelets (GNs) (average diameter: >50 nm; average length: 20 μm ; purity: >92 wt%). It suggested that better the aggregation effect of dispersed particles was, the more significant the shear thickening effect achieved. The results also revealed that the formation of large nanomaterials clusters could be suitable to explain the phenomena. Furthermore, the trend of shear thickening behavior of the silica suspension with CNTs was more striking than that of GNs. The physical reactions between those multi-dispersed phases had been described by the schematic illustrations in papers. Otherwise, a model was built to explain these behaviors, which could be attributed to the unique structures and inherent properties of these two different nanofillers. And the morphologies of the shear thickening

fluid which were examined by transmission electron microscopy confirmed this mechanism.

Keywords Shear thickening behavior · Nanofillers · Rheological property · Model · Mechanism

Introduction

Shear thickening behavior, accompanied with significant, discontinuous steep increase in viscosity, is a generic phenomenon existing in concentrated colloidal suspensions when they are subjected with increasing shear rate or applied stress (Tarig et al. 2010). And much effort has been focused on the mechanism of this shear thickening behavior. The explanations offered for the phenomenon that are supported by independent physical measurements, which proposed that the increase in viscosity is due to the transition from a two-dimensional layered arrangement of particles to a random three-dimensional form (Barnes 1989). Many research groups have conducted intensive studies of the rheological properties of shear thickening flow (STF) under steady and dynamical conditions. Thus, in pioneering work, two main causes of this shear thickening behavior have been reported in the literature: the order–disorder transition (Hoffman 1974) and the “hydroclusters” mechanism (Bender and Wanger 1996). Hoffman (1972) proposed that the occurrence

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of shear thickening behavior in concentrated dispersions resulted from a transition of an easy flowing state (where the particles are ordered in layers) to a disordered state called “order–disorder” transition. However, it has been argued by subsequent researchers that it is not at all necessary to assume the existence of an ordered state before the shear thickening transition. With the Stokesian dynamics simulation, Bossis and Brady (1989) and Boersma et al. (1992) demonstrated that the shear thickening behavior in concentrated colloidal suspensions is caused by hydrodynamic lubrication forces between particles, resulting in the formation of a nonequilibrium, self-organized microstructure that develops under strong flows, denoted as “hydroclusters”. More recently, the model of “jamming transition” was also introduced in this field. It was suggested that the shear thickening behavior is the consequence of jammed particles due to the confinement (Holmes et al. 2003; Brown and Jaeger 2009), which was apparently in contrast to the negative normal stress as derived from hydrodynamic mechanisms (Singh and Nott 2003). In addition, Masashi Kamibayashi et al. (2008) demonstrated the polymer bridging (Iler 1971; Fler and Lyklema 1974) mechanism that when the polymer coils containing several nanoparticles are subjected to high-shear fields, three-dimensional network is developed over the system and shear thickening behavior was observed due to the restoring forces of extended bridges. Among these models, there is agreement in the shear thickening that the macroscopic properties of dispersions are determined by the spatial organization of the particles which are usually defined as “microstructure”. Although a significant number of experimental and theoretical studies have been made, the detailed mechanism of this shear thickening behavior is still under debate (Fall et al. 2008).

Rheological properties of STF depend on varieties of factors, especially the nature of nanoparticles and the solvent (Xu et al. 2010). The interaction between nanoparticles and solvent was connected by the molecular chain and functional groups of nanoparticles and solvent (Sarvestani and Picu 2004). When additive with long chains come into contact with surface of bare nanoparticles, the bonds of polymer chains are formed between those nanoparticles (Iler 1971; Fler and Lyklema 1974). It has been reported that besides the nanoparticles, the additive is another important factor influencing rheological properties of

STFs (Kamibayashi et al. 2008). Many researchers have studied the size (Maranzano and Wagner 2001a, b) and types (Egres and Wagner 2005; Jiang et al. 2010; Li et al. 2011) of the dispersed medium influencing on the shear thickening behavior. In pioneering works, it has revealed that the actual nature of the shear thickening will be affected by the volume, size (distribution), and shape of the particles. The severity of shear thickening was also demonstrated to depend on the concentration, in proportion to some maximum packing fraction partly controlled by the form of the particle size distribution (Barnes 1989).

However, actually it is difficult to obtain the high weight fraction of STFs in most preparation process, due to the extensive aggregation of nanoparticles. How to solve this problem through a simple and common method? During the study process of STFs, we found that in most cases, the spherical nanoparticles were usually used as the single suspended phase, no matter the silica nanoparticles or the other types of nanofillers. Considering the influence factors of STFs, we have started from the silica nanoparticles by surface treatment with ethylene glycol to solve this problem in our previous work (Yu et al. 2012). Though the effect of surface treatment on STFs was remarkable, is there another way to solve this problem? Based on the pure STFs comprised of silica nanoparticles as the single-suspended phase, what would happen if we added another shape of nanofillers as the second suspended phases? In this study, in order to improve the shear thickening behavior of silica suspensions and obtain the multifunctional materials, carbon nanofillers are chosen in our study. Carbon materials have received increasing interest in material science. They are widely used as nanofillers in polymer composites or suspensions to improve electrical, thermal, and optical properties of the carriers (Ajayan et al. 2000; Hu et al. 2011; Chen and Yan 2010; Sheng et al. 2011). Carbon nanofillers mainly exist in four types: carbon black, graphite, carbon fibers, and carbon nanotubes (CNTs), and each type have their own characteristics. The use of a combination of different carbon nanofillers would be a good way to get balanced properties. CNTs and graphene nanoplatelets (GNs) are chosen in our papers, as they both possess unique nanostructures with remarkable physical and mechanical properties (Iijima 1991; Novoselov et al. 2004; Geim and Novoselov 2007; Song et al. 2011; Soldano et al. 2010; Luong et al. 2011; Rafiee et al. 2009; Park and Ruoff 2009).

The steady shear thickening behaviors of concentrated dispersions are systematically studied with these two types of carbon nanofillers. This study aims at a better understanding of the rheological properties of the silica nanosuspensions with different dispersed phases, trying to explore how the carbon nanofillers work in STF and whether they can make a contribution to the improvement of the shear thickening behavior. Although far from the complexity of multi-suspended phases in shear thickening fluids, we believe that studies of simple model systems are an important complement to interpret the influence mechanism of the micro-structures and properties.

These novel shear thickening fluids might, for example, pave the way for gaining better understanding the mechanism of shear thickening behavior. Another aspect relating to the present study is the potential application with carbon-based materials in shear thickening fluids systems, and the development of structure-viscosity relationship to get the parameters for preparation of remarkable shear thickening fluids. The carbon nanofillers provide the STFs with a variety of properties such as electric, optics and calorifics, so that these STFs can be used to prepare the multifunctional composite materials. Furthermore, in order to investigate the possible interaction between silica and nanofillers in these high-viscosity STFs, the colloidal properties of these STFs will be of great interest (Zakaria et al. 2013; Wang et al. 2012). And this study of the interactions mechanism between silica and nanofillers will also make a significant contribution to colloid research.

Experimental

Materials

The materials used in this study include dry powder of spherical silica nanoparticles (average diameter: 650 nm) purchased from Evonik Degussa Co., Ltd. (China). Polyethylene glycol (PEG) used as the solvent in STFs was supplied by Sinopharm Chemical Reagent Co. Ltd. (China). The average molecular weight of PEG used in this study is 200 g/mol. GNs (average diameter: >50 nm; average length: 20 μm ; purity: >92 wt%) and CNTs (main range of diameter: 10–20 nm; length: 5–15 μm ; purity: >97 wt%) were purchased from Shenzhen Nanotech Port (China). The

densities of GNs and CNTs were 2.25 g/cm³ and 1.71 g/cm³, respectively.

Preparation of shear thickening fluids

The various STFs were prepared as follows: (1) the silica nanoparticles were dissolved in PEG to obtain the basic solution. (2) GNs (or CNTs) were dispersed in (1) solution. (3) In order to obtain a uniform distribution of silica nanoparticles within the suspension and ensure the nanoparticles were not aggregated, the mixture was stirred for about 4 h with the speed of 400 rpm while at the same time.

Characterization

Transmission electron microscopy (TEM)

The suspension droplet was diluted with ethylalcohol at the ratio 1:100 and sonicated for 1 h. Ethylalcohol was used as dispersion medium because of its high volatility, low toxicity, low viscosity, and similar structure to PEG. Morphologies of nanoparticles of STFs were observed on copper mesh by transmission electron microscope (TEM, JEM-2100, JEOL, Japan). Images of nanoparticles were taken at 10⁴× magnification.

Rheological tests

Rheological measurements of STF suspensions were performed at 25 °C using a stress-controlled rheometer ((Rheometrics, Anton-Paar Physica MCR 301, Austria) with a plate geometry (cone diameter = 50 mm, gap = 1 mm). For each measurement, 2 mL of the suspension sample was loaded on the rheometer. The viscosity of suspensions was measured by a steady state flow program with the shear rate ranging from 0.01 to 200 s⁻¹ during 6 min.

Results and discussion

Microstructure analysis

TEM was used to study the dispersion behavior of different nanoparticles types. Figure 1 shows the TEM images of four types of nanoparticles in dispersed phase. As shown in Fig. 1a, it was clear that most of silica particles were spherical and in good

monodispersity, most of the particles were self-existence in dispersing medium, so that the viscosity of the suspensions should be low. It could be inferred that it might take a long time for silica particles to aggregate under applied stress. Silica particles after mixed with other nanoparticles showed extensive aggregations in PEG (Fig. 1b, c, d). In Fig. 1b, the GNs took silica on their surface as their special forms. Several silica particles took a piece of GNs as a carrier in suspensions, so that the particles were divided into small groups as observed. The situation also appeared in the suspensions with CNTs owing to the winding effects between nanotubes and silica particles.

While the suspensions were mixed with GNs and CNTs simultaneously, the integration of these three dispersed phase was more close (arrows in Fig. 1d) and the internal force of their unit was stronger. The units of

those three dispersed phases may make the viscosity of the mixed suspensions higher and short the road to form the “hydroclusters”. TEM analysis was also in good conformity with the models shown in Fig. 4. The TEM images confirmed that physical reactions between silica and nanoparticles had been occurred as designed.

Rheological properties of STFs

To further study the influence of the two carbon nanofillers on the shear thickening behavior of the silica nanosuspensions in practical experiments, rheological tests were carried out on a rheometer in steady modes. Figure 2 showed the shear rate dependence of viscosity for suspensions of 650 nm silica in 75 wt% solution of PEG-200 at different particle concentrations of GNs and CNTs.

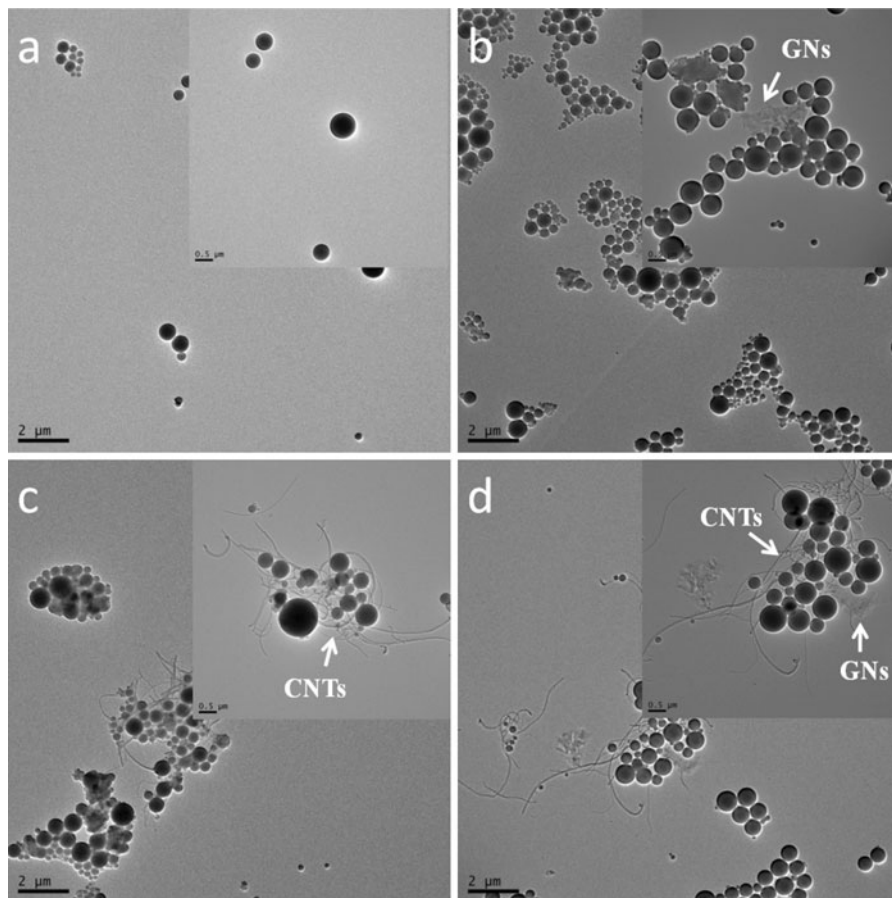


Fig. 1 TEM images of different nanoparticles in dispersed phase **a** silica, **b** silica and GNs, **c** silica and CNTs, and **d** silica, GNs, and CNTs

As shown in Fig. 2, the viscosities of each sample tend to decrease with increasing shear rate in the beginning. However, the viscosity had an abrupt discontinuous jump to higher level while approaching to the critical points of shear rate, which marked to the transition to shear thickening behavior. Once shear stress exceeded the maximum allowable torque moment of the rheometer, the test was automatically stopped as a result of the strong shear thickening effect. In practice, the samples turned into solid state while the GNs concentrations reached to 4 wt% and the CNTs concentrations to 3 wt%, and the measurements had to be finished at this two ratios. At a silica particle concentration of 75 wt%, the suspensions acted as the basic system without GNs and CNTs had shown a non-Newtonian flow profile. The additions of GNs and CNTs made the mixtures represent different degrees of shear thickening behaviors. It was noted that the increase of viscosity due to the particles concentrations was very obvious for all samples, which would impact the shear thickening effect. Moreover, it could be observed that the critical thickening points had some shifts, some shift to lower shear rates due to the higher particle concentrations and some shift to higher shear rates as the lower particle concentrations. In both cases of GNs and CNTs, the viscosity at the same shear rate point during the shear thickening process tends to increase with increasing particle concentrations, while the critical shear thickening rate began to decrease. Compare with the samples without GNs and CNTs, it was obvious

that GNs and CNTs both had a positive effect on the shear thickening improvement.

On the other hand, to investigate the difference between the STFs with GNs and CNTs acted as dispersed phase, the curves of the same particle concentrations could be compared in Fig. 2. It could be seen that the additions of CNTs caused higher viscosity increase over the entire range of shear rate than that of GNs at the same particle concentrations. The impact of CNTs at the particle concentrations of 1 wt% on the rheological properties was similar to that of GNs at the particle concentrations of 2 wt%, and the incremental changes of viscosities in different particle concentrations of CNTs were bigger than that of GNs. It could be inferred that CNTs played a more significant role as dispersed phase in rheological properties of STF.

How about the rheological properties of the silica suspensions with both CNTs and GNs? The suspensions comprised of both CNTs and GNs at different particle concentrations were prepared to compare with the single-additive silica suspensions, and the particle concentrations of the additives in suspensions were 3 wt% in total. As shown in Fig. 3, it can be seen that the viscosity was highest in all samples when the particle concentration of CNTs got to 3 wt%. However, the viscosity of STF with 3 wt% GNs was the lowest. And the curves of the other mixed STFs were located between the two curves of single-carbon nanofiller suspensions.

In those multi-additive STFs, while the proportion of GNs was larger than that of CNTs, the trends of the

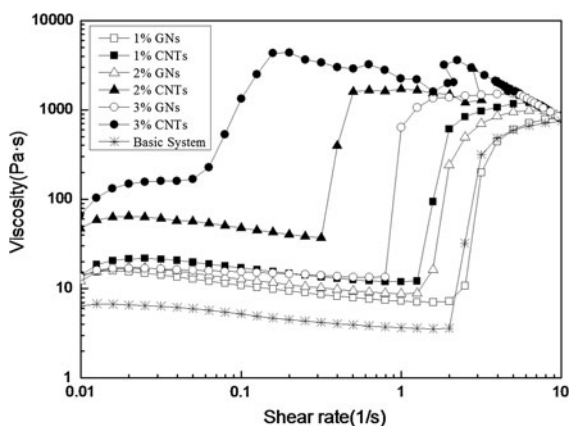


Fig. 2 Steady shear thickening behavior of the STFs with different particle concentrations of GNs and CNTs

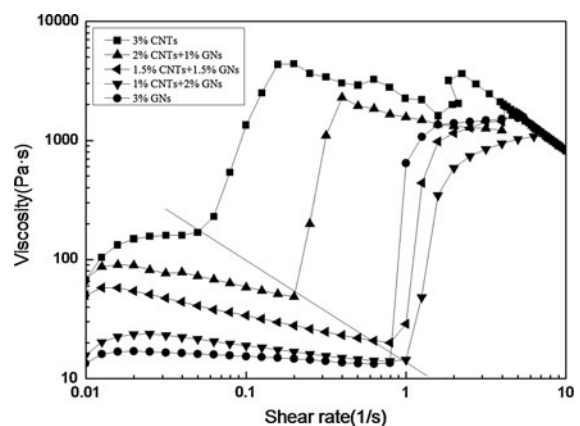


Fig. 3 Steady shear thickening behavior of the STFs comprised of GNs and CNTs with different ratios

shear thickening curves were similar to the one with 3 wt% GNs. On the contrary, while the proportion of the CNTs was larger, it was obvious earlier for shear thickening behavior to take place due to the leading effect of the CNTs. Therefore we found that the one who had a larger proportion among these two additives would play a leading role in the mixed system.

In terms of image, we could propose that CNTs play a positive role in the mixed system while GNs have a negative effect. As we know, the high viscosity of the STFs with only CNTs made it earlier for shear thickening behavior to take place (such as the highest curve shown in Fig. 3), which limited the range of applications. Moreover, the viscosities during the shear thinning period were too high and resulted in difficulty for the preparation and production in real manufacture process. In view of the different effects of CNTs and GNs, they could play different roles in STF systems. For example, once the viscosity of the suspensions with CNTs was too high, the addition of the GNs would help to reduce the viscosity of the STF system.

In these cases, CNTs could help to make the occurrence of shear thickening behavior earlier in the suspensions, and GNs were possible to reduce the exorbitant viscosity of the suspensions with only CNTs. Among these tests, when the basic system was adding 2 wt% CNTs and 1 wt% GNs, the synergistic effect was remarkable and suitable for the preparation and production. It might be inferred that combinations of CNTs and GNs would win the perfect effect of the shear thickening behavior.

It had been reported that the rheological curves were fitted to a power law model (Lei et al. 1994). For shear thickening fluids, the relationship between the shear stress Σ (Pa) and shear rate γ (1/s) could be fitted by a power law relation as follows

$$\Sigma = K \cdot \gamma^n \quad (1)$$

where K was the consistency index (Pa s^n), and n was the index that provided information about the flow behavior related to the effect of shear rate. And the relationship between viscosity η (Pa s) and shear stress Σ was given

$$\eta = \frac{\Sigma}{\gamma} \quad (2)$$

It could be inferred that

$$\eta = K \cdot (\gamma)^{n-1} \quad (3)$$

There existed three value ranges for n : $n < 1$ for a shear-thinning fluid, $n = 1$ for a Newtonian fluid, and $n > 1$ for a shear thickening fluid. Table 1 shows the rheological parameters fitted with a power law function for STFs with different particle concentrations of GNs and CNTs.

As the data listed in Table 1, the consistency coefficient indices (K), no matter K_1 or K_2 , were increased greatly, it had been reported that the larger the K , the more viscous the fluid was (Dong et al. 2009). It was obvious that both of the GNs and CNTs had a positive effect on the increasing viscosity, and the CNTs did a better job in increasing the viscosities. The K values increased for the suspensions formulations, in agreement with the increase of viscosity according to the flow curves in Fig. 3. Furthermore, it was reported that for pseudoplastic fluid, $n > 1$, for the dilatant fluid, $n < 1$, and for the Newtonian fluid, $n = 1$ (Yang et al. 2009). As also could be seen from Table 1, it was obvious that in the shear-thinning region, the shear flow exponent values (n_1) were all < 1 and fluctuated around 0.85, suggesting their shear-thinning nature and low variability in this region. However, when shear thickening occurred, the shear flow exponent values (n_2) showed a steep jump to a higher value to some extent, all values obtained were > 1.0 , further indicating the shear thickening nature of the nanosuspensions. For the different series of suspensions, the value of n_2 decreased. For example, in suspensions with GNs, n_2 changed from 4.05 to 1.39, which demonstrated a less apparent non-Newtonian nature for suspensions with the increasing particle concentrations of additions. The n_2 value indicated the degrees of the shear thickening behavior, the larger the n_2 , the more apparent the shear thickening behavior should show. However, the nascent viscosity increased greatly with the increasing of the different particle concentrations which lead to a lower increase of viscosity after the critical point. In another word, the increasing K values which indicated the increasing of the overall viscosities in the suspensions lead to the decreasing of n_2 values. This inversely proportional relationship could be confirmed in Table 1. The situations in suspensions with CNTs were similar to GNs. And we could find that carbon nanotubes also played a more important role than GNs at the same mass fraction of additions in the mixed suspensions with both CNTs and GNs.

Table 1 Rheological parameters obtained from fitting using power law model for STF's with different particle concentrations of GNs and CNTs

Dispersed phase	Particle concentrations (wt%)	K_1 (Pa s ^{<i>n</i>})	K_2 (Pa s ^{<i>n</i>})	n_1	n_2
Silica	75	3.62	1.40	0.85	4.49
Silica+GNs	75 + 1	7.16	2.01	0.81	4.05
	75 + 2	8.50	21.14	0.83	2.99
	75 + 3	13.15	379.50	0.93	1.69
	75 + 4	20.33	808.72	0.94	1.39
	75 + 5	30.15	1512.50	0.95	1.19
Silica+CNTs	75 + 1	11.73	70.89	0.85	2.45
	75 + 2	31.37	1329.30	0.86	1.12
	75 + 3	515.95	1889.20	0.93	1.10
Silica+GNs+CNTs	75 + 1 + 2	34.52	1224.10	0.77	1.01
	75 + 1.5 + 1.5	18.12	209.42	0.79	2.09
	75 + 2 + 1	13.62	92.74	0.87	2.19

Model of the mechanism

The schematic illustrations of physical reactions of the nanoparticles with each others in the suspensions could be gained from Fig. 4, which could explain how those nanoparticles work in the dispersing medium. As illustrated in Fig. 4a, the silica particles were dispersed well in mediums in the beginning, the occurrence of shear-thinning behavior resulted from the disordered state of the particles under the applied stress. With the increasing shear rate or stress, the particles turned to aggregate caused by hydrodynamic lubrication forces to counteract the outside force. After the removal of impact stress, the suspensions turned back to be an easy flowing state.

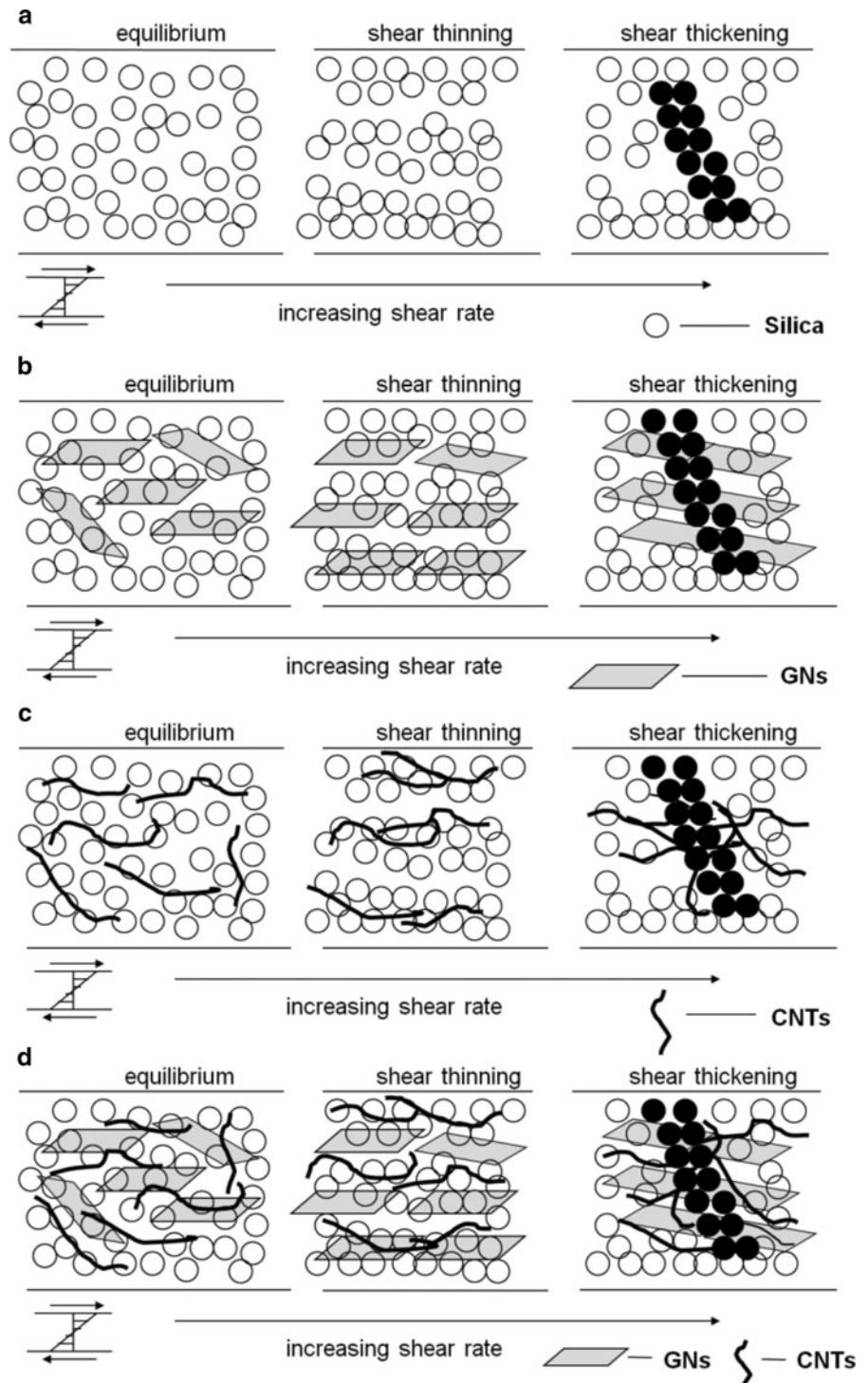
The interactions between the nanoparticles were strong due to the huge surface energy of nanoparticles. There were three competing interactions in the system when nanoparticles were mixed with polymers (PEG). The first was the interaction for a PEG-PEG contact (P-P), the second was the interaction for a nanoparticle-nanoparticle contact (N-N), and the third was the interactions for a PEG-nanoparticle contact (P-N). The first and second interactions would cause the phase separation of PEG and nanoparticles, which was conducive to the aggregation of nanoparticles. In Fig. 4b, the GNs acted as a "bridge" between the silica particles. The layers took the silica particles as "passengers" on their surfaces which resulted from the strong interactions such as hydrogen bonds, π bonds, or Vander Waals force between the nanoparticles due to their specific structures and functional groups. And the expeditious aggregations lead to an

obvious shear thickening behavior at low-shear rate. The difference in the suspensions of GNs and CNTs was caused by the interaction between the nanoparticles and PEG. P-P and N-N were almost the same for GNs and CNTs as they had the same elements-carbon and the structures of C-C were similar for both GNs and CNTs. The difference arose from the P-N.

The difference between GNs and CNTs lay in the shape of these two nanoparticles. The CNTs showed like tubes as its name while the graphene look like sheets. PEG used as dispersing medium was a kind of polymer with long chemical chains. The relative lubrication forced between CNTs and PEG were stronger than that between GNs and PEG because of the similar structure of CNTs and PEG, which implied that the internal force of P-C (C represents CNTs) was much weaker than P-G (G represents GNs) (Hu et al. 2012). The phase separations of the dispersing medium and nanoparticles would exist earlier in suspensions with CNTs, so did the shear thickening behavior.

On the other hand, it was noted that the interactions between silica and GNs were brought by the surface friction, while the aggregations more likely occurred between CNTs and silica particles due to their winding effects (Fig. 4c). The shear thickening behavior was easier to take place in suspensions with CNTs than that with GNs at the same mass fraction. In this manuscript, for the two kinds of the carbon nanofillers (Fig. 4d), the CNTs were used as one-dimensional "rigid-rod" carbon nanofillers, while GNs were used as two-dimensional "soft" carbon nanofillers. As a result of the different structures of nanostructure and

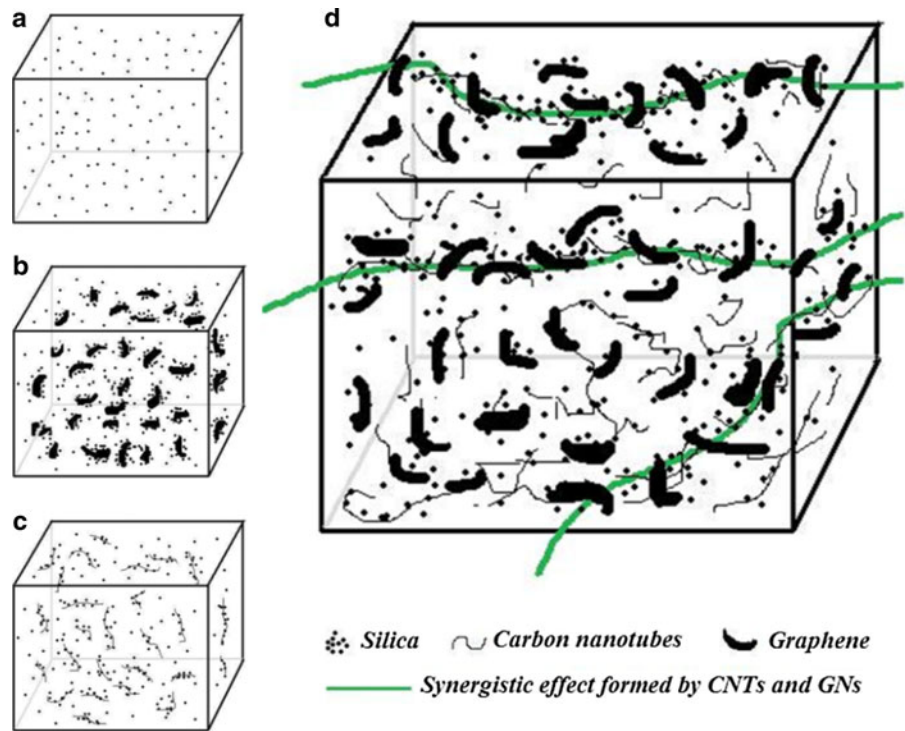
Fig. 4 Schematic illustrations of physical reactions of the nanoparticles with each others in STFs **a** silica, **b** silica and GNs, **c** silica and CNTs, and **d** silica, GNs, and CNTs



internal structural rigidity of these two carbon nanofillers, the use of a combination of the two different carbon nanofillers would be a good way to get

balanced properties. This imagination was in good agreement with previously results of the tests in Table 1.

Fig. 5 Model of the formation of cosupporting GNs/CNTs synergistic effect **a** silica, **b** silica+GNs, **c** silica+CNTs, and **d** silica+GNs+CNTs



On the basis of the fact that the two carbon nanofillers both had a positive effect on the shear thickening improvement, a model was proposed by extending the “hydroclusters” mechanism (Bossis and Brady 1989; Boersma et al. 1992). Different from the traditional models of STFs, our models tried to describe the mechanism of multi-fillers-filled STFs systems, discovering the different states between diverse dispersed phases of STFs in visual. In the building up of the model, the excluded volumes of the two fillers were kept constant in single-filler-filled and mixed-filler-filled systems. Thus, we assumed that the dispersions of the three dispersed phase were not affected by the presence of each other in our models. Regard the silica suspensions as an original model system (Fig. 5a), it was reported that the relationships between weight fractions and percolation concentrations in two-filler-filled polymers had been demonstrated by Sun et al. (2009). According to the extended excluded volume theory, for a system containing two types of conductive fillers such as A and B, we had the following equation

$$\frac{V_A}{\phi_A} + \frac{V_B}{\phi_B} = 1 \tag{4}$$

where V_A and V_B were the volume fractions of fillers A and B, respectively, and ϕ_A and ϕ_B were the percolation concentrations of A and B expressed in volume fraction if the unit volume was filled with A or B alone. Supposing there was only one type of conductive filler (shown in Fig. 5b, c), from Eq. 4, we could infer the volume fractions of fillers V_X were proportional to percolation concentrations ϕ_X . As in the comparison tests of those two nanofillers with the same mass fraction, the volume fraction could be generalized as fillers’ density for the convenience of practical in our models, therefore, the fillers’ density ρ_x was inversely proportional to percolation concentrations ϕ_x that was

$$\rho_x \propto \frac{1}{\phi_x} \tag{5}$$

Which indicated the higher the fillers’ density was, the lower its percolation concentrations would be. In our tests, we had obtained the densities of the three dispersed phase, the densities of GNs and CNTs were 2.25 and 1.71 g/cm³, respectively. From the data, it was clear that the density of CNTs was lower than that of GNs, that was $\rho_C < \rho_G$, where ρ_C and ρ_G were the densities of fillers CNTs and GNs. If the unit volume was filled with

CNTs (Fig. 5c) or GNs (Fig. 5b) alone, from Eq. 5, we might have $\phi_C > \phi_G$, which indicated more numbers of CNTs would infiltrate through in the unit volume to do a better job on the improvement of shear thickening behavior than GNs. For systems containing both two different types of carbon nanofillers CNTs and GNs (Fig. 5d), the CNTs with long aspect ratio acted as long-distance charge transporters, and the disk-like GNs served as an interconnection between the tubes by forming synergistic effect. The cooperation of CNTs and GNs made progress on the aggregation effect and was the best way to make use of space as possible as they could. And it could be imagined that CNTs would have the call in this meliorative work. The conclusions developed from the equation and models fitted the experimental results well, and were useful for describing the different states and functions of these two carbon nanofillers in suspensions.

Conclusions

In this study, we modified the nanoparticles suspensions with two kinds of carbon nanofillers and investigated the rheological behavior of the relevant silica suspensions in PEG. A model describing the reactions between the suspensions and carbon nanofillers (GNs and CNTs) was proposed on the basis of the excluded “hydroclusters” mechanism. First, the silica nanoparticles suspensions without fillers also showed shear thickening behavior under high-shear rate. Second, the additions of GNs and CNTs both had an effect on improving the degree of shear thickening by increasing their weight fractions. Third, CNTs made a more significant contribution than GNs at the same mass fraction on the shear thickening behavior improvement due to its specific tubular structure. Last, the combination of these two carbon nanofillers could win the perfect effect. More experimental data, however, were still needed to better understand and interpret the influence mechanism of the micro-structures and properties.

Acknowledgments This work was supported by the National Natural Science Foundation of China (No. 51203062), Cooperative Innovation Fund-Prospective Project of Jiangsu Province (No. BY2012064), and Science and Technology support Project of Jiangsu Province (No. BE2011014). K.J. Yu thanks the Postdoctoral Fund Project of China (No. 2012M520995).

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