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Abstract

The rheological properties of shear thickening fluid (STF) reinforced with SiC nanowires were investigated in this paper. Pure STF consists of 56 vol% silica nano-particles and polyethylene glycol 400 (PEG 400) solvent was fabricated; and a specific amount of SiC nanowires were dispersed into this pure STF, and then the volume fraction of PEG400 was adjusted to maintain the volume fraction of solid phase in the STF at a constant of 56%. The results showed there was almost 30% increase in the initial and shear thickening viscosity of the STF reinforced with SiC nanowires compared to the pure STF. Combining with the hydrodynamic cluster theory, the effect of the mechanism of SiC nanowire on the viscosity of STF was discussed, and based on the experimental results, an analytical model of viscosity was used to describe the rheological properties of STF, which agreed with the experimental results.

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The rheological properties of shear thickening fluid reinforced with SiC nanowires

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ABSTRACT

The rheological properties of shear thickening fluid (STF) reinforced with SiC nanowires were investigated in this paper. Pure STF consists of 56 vol% silica nano-particles and polyethylene glycol 400 (PEG 400) solvent was fabricated; and a specific amount of SiC nanowires were dispersed into this pure STF, and then the volume fraction of PEG400 was adjusted to maintain the volume fraction of solid phase in the STF at a constant of 56%. The results showed there was almost 30% increase in the initial and shear thickening viscosity of the STF reinforced with SiC nanowires compared to the pure STF. Combining with the hydrodynamic cluster theory, the effect of the mechanism of SiC nanowire on the viscosity of STF was discussed, and based on the experimental results, an analytical model of viscosity was used to describe the rheological properties of STF, which agreed with the experimental results.

Introduction

Shear thickening fluid (STF) is Non-Newton fluid, in which the hard nanoparticles are dispersed in the carrier fluid. The viscosity of STF can increase dramatically to become almost solid when the shear rate exceeds a critical value [1,2]. Because of its unique characteristics, STF has been used to develop energy absorbers, vibration controllers and safety protects [3–11]. For instance, Petel et al. [7] investigated how the particle strength and volume fraction affected the deceleration performance of STF. Lu et al. [8] studied the compressive behavior of warp-knitted fabrics impregnated with shear thickening fluid. Park et al. [9] experimentally and numerically investigated the absorption properties of Kevlar fabrics impregnated by STF at a velocity between 1 to 2 km/s. Tan et al. [10] studied the energy absorption characteristics of a sandwich plate with an STF core subjected to penetration loading. Fisher et al. [11] reported the effect of a STF core on the vibration suppression of a sandwich beam. In a bid to further improve its application, fabricating STF with a high rheological performance presents a significant challenge.

Among those works focused on the application of STF, several of them aimed at improving the rheological performance of STF in order to enhance the application of STF [12–15]. Feng et al. [12] studied the effect of STFs with sub-micrometer silica and fumed silica particles on quasi-static stab resistant properties of fabrics impregnated with shear thickening fluids. Laha et al. [13] investigated the effect of the silica-halloysite nanotubes on the properties of STFs. Gürgen et al. [14] investigated the influence of ceramic particle additives on the STF consisting of fumed silica and PEG400.

These previous works showed that the shear thickening mechanism of STF forms internal chains or clusters of nanoparticles [15–17]. Based on those previous works, the SiC nanowires were used to promote the 56 vol% pure STF. Different amount of SiC nanowires were added into the pure STF. To study the role that SiC nanowires play in STF, the total volume fraction of the SiO_2 and SiC nanowires are kept at a constant 56 vol%. The rheological behavior of STF reinforced by SiC nanowires is tested and compared to STF without nanowires. The effect that nanowire has on the viscosity of the STF was then discussed. An analytical model was also used to fit the experimental results, which means it can be used for future numerical calculations.

Experimental procedures

Materials

Pure STF in this study consists of SiO_2 nano-particles and polyethylene glycol with a molecular weight of 400 (PEG400). The SiO_2 sphere with a diameter of 300 nm, made by Stober methods

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[18,19], was tested using an S-4800 field emission scanning electron microscope (FE-SEM), as shown in Fig. 1(a). SiC nanowire (produced by Nanjing XF Nano Company in China) was used to improve the pure STF fabricated with SiO_2/PEG400. An SEM graph of SiC nanowires is shown in Fig. 1(b).

The pure STF with 56 vol% SiO_2 nanoparticles was fabricated with a specific volume of SiO_2 nano-particles and PEG400 solvent; it was then treated in a planetary ball mill for 2–3 h. Based on pure STFs, SiC nanowires were added into the pure STF to improve its viscosity. This dispersed phase (including SiC nanowires and SiO_2) volume fraction was kept constant at 56%. The process is as follows: (1) a specific amount of SiC nanowires were added into pure SiO_2/PEG400 STF to ensure that the volume fraction of the dispersed phase was 56 vol%; (2) the STF and SiC nanowires were mixed with ethyl alcohol for 40mins using a sonicator to ensure a uniform dispersion of SiC nanowires and SiO_2 nanoparticles in the PEG/400 and alcohol solvent; (3) this fluid was then placed inside a dry box for 24 h at 65 °C to remove ethyl alcohol. In order to analyze the effect that SiC nanowires have in STF, three types of STFs were designed in these experiments. The volume fraction of the SiC nanowires is 0.625 vol%, 0.938 vol%, and 1.25 vol%, respectively. Details of these samples are shown in Table 1.

Rheology test

Rheology tests were carried out using a rheometer (Anton-Paar MCR301) at the University of Science and Technology of China. The samples were placed between a cone plate and foundation support of the rheometer. The angle and diameter of cone plate is 2.007° and 24.967 mm, respectively. The shear rate applied on the sample was increased from 0 to 100 s^{-1} during the experiments. All the tests were carried out at room temperature of 25 °C.

Results and discussions

Viscosity-shear rate curves

The viscosity curves of the four different STFs shown in Fig. 2 indicate that each curve has three processes: shear thinning, shear thickening and shear thinning. Both initial and the shear thickening viscosities of the STFs with SiC nanowires have significant increases compared to the STF without SiC nanowires. This initial viscosity increases as the volume fraction of SiC nanowires increases. The initial viscosity of the STF without SiC nanowires is about 50 Pa·s, and the initial viscosity of the STF reinforced with SiC nanowires is about 300 Pa·s, 550 Pa·s and 755 Pa·s; this increase was due to SiC nanowires, even though the critical shear rate is similar.

All four of these STFs experienced obvious discontinuous shear thickening, during which process the maximum viscosity increased and then decreased as the volume fraction increased. The peak value of the pure STF is 460 Pa·s, and the peak values of the STF with 0.625 vol%, 0.938 vol% and 1.25 vol% SiC nanowires are 605 Pa·s, 620 Pa·s, and 462 Pa·s, respectively. Compared to the pure STF, the increase in the viscosity of the STF with SiC nanowires is about 30%.

To illustrate the improvement in the viscosity of STFs, we defined this ratio (ϕ) as:

$$\phi = \frac{\eta_{i\max} - \eta_{A\max}}{\eta_{A\max}}\% \quad (i = B, C, D) \tag{1}$$

where, $\eta_{A\max}$ and $\eta_{i\max}(i = B, C, D)$ are the maximum viscosities of the STF samples A, B, C and D during the shear thickening period. The results are shown in Fig. 3.

Effect of the SiC nanowires on the viscosity

It can be seen from Fig. 2 that there is a significant influence on the viscosity of the STFs by the SiC nanowires. Fig. 4 is a schematic graph of the mechanism of the shear thickening and shear thinning of the STF with/without nanowires.

For the STF without nanowires, the shear thickening mechanism of the STF is due to the formation of jamming clusters bound together by hydrodynamic lubrication force [17–19]. As the shear rate increases, the hydrodynamic lubrication force cannot bear the external force so the nanoparticles begin to slip and the jamming clusters collapse, as shown in Fig. 4(a).

The nanowires in STF at a quasi-static or at a less than critical shear rate, were distributed between the nanoparticles, so they cannot flow inside the STF, which caused the quasi-static viscosity to increase as the volume fraction of SiC nanowires increased. This scenario corresponds to the large increase in viscosity at a quasi-static shear rate shown in Fig. 2.

When the shear rate reaches a critical value, the viscosity increases immediately due to the formation of particle clusters. And then the nanowires between the clusters of nanoparticles will prevent them from slipping and collapsing; this will increase the viscosity of STF, as shown in Fig. 4(b), which corresponds to an increase in the viscosity of STF with 0.625 vol% and 0.938 vol% SiC nanowires, as shown in Fig. 2.

However, if the amount of SiC nanowires is excessive, the nanoparticle clusters would contain many nanowires, which weakens the clusters and makes it easier for the nanoparticles to slip, as

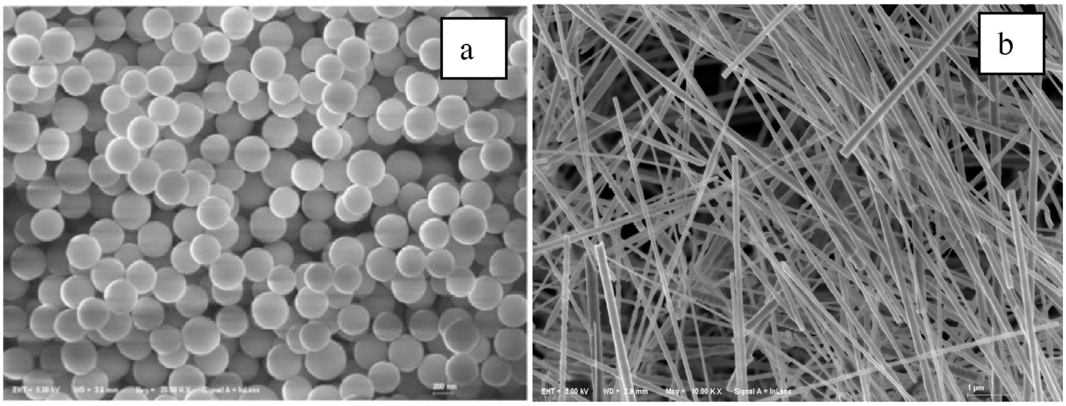

Fig. 1. The SEM graphs of (a) SiO_2 particles and (b) SiC nanowires.

Table 1
The volume fraction of the dispersed phase in the different STFs.

Sample No.	A	B	C	D
The volume fraction of SiC nanowires (vol%)	0	0.625	0.938	1.250
The volume fraction of SiO_2 (vol%)	56	55.375	55.063	54.750
Total volume fraction of the dispersed phase (vol%)	56	56	56	56

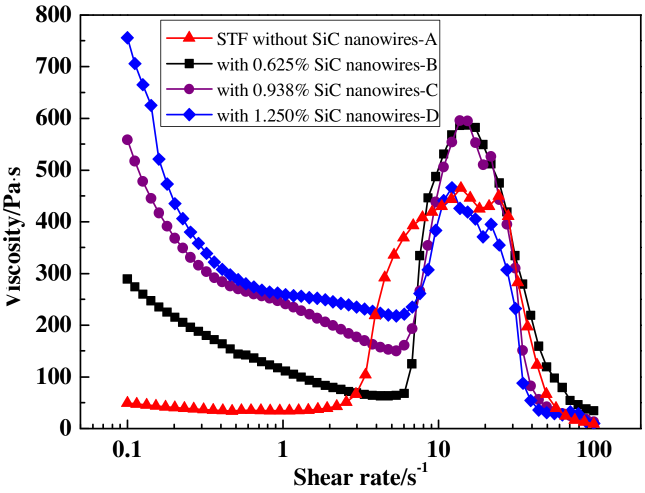

Fig. 2. The curves of viscosity vs. shear strain rate of samples A, B, C and D.

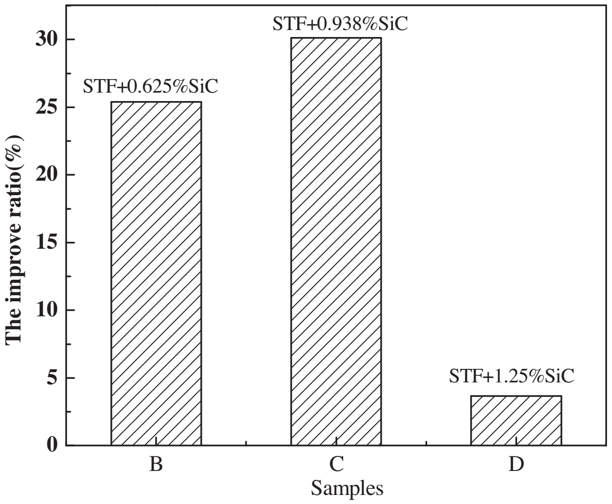

Fig. 3. The improve ratio of viscosity of different STFs compared to the pure STF.

shown in Fig. 4(c). This result corresponds to the decreasing viscosity of the STF with 1.25 vol% compared to that of the STF with 0.625 vol% and 0.938 vol% SiC nanowires shown in Fig. 2.

Analytical model

A viscosity model was used to fit the experimental results; further can be found in Ref. [20]. This model is useful for numerical simulations and curve-fitting procedures due to its continuous derivative. It contains a three part function which can be used to model the three typical regions shown in Fig. 2. The model is expressed as follows:

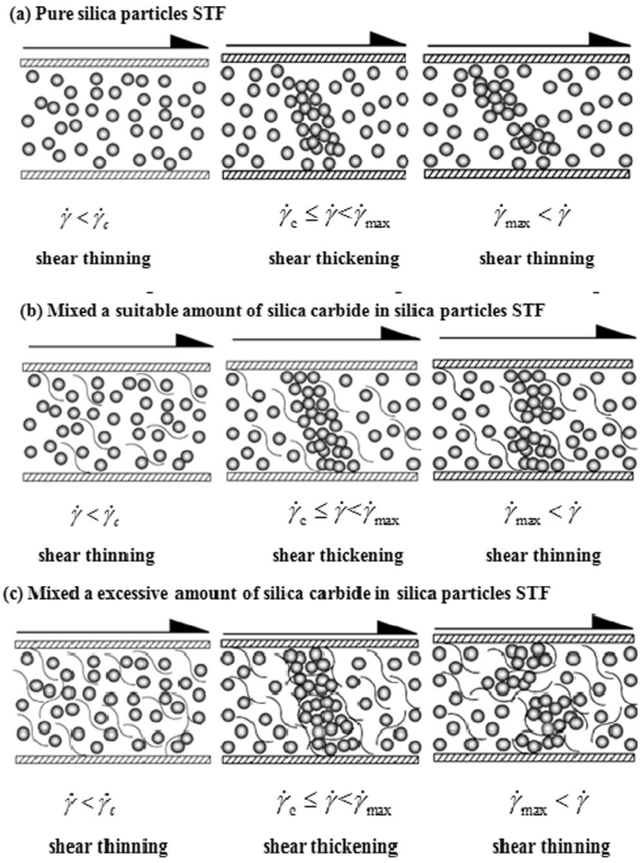

Fig. 4. Schematic graph of the mechanism of the shear thickening. (a) pure STF; (b) STF with a proper amount of SiC nanowires; (c) STF with an excessive SiC nanowires.

$$\eta(\dot{\gamma}) = \begin{cases} \eta_{\mathrm{I}}(\dot{\gamma}) = \eta_c + \frac{\eta_0-\eta_c}{1+[K_{\mathrm{I}}(\dot{\gamma}^2/(\dot{\gamma}-\dot{\gamma}_c))]^{n_{\mathrm{I}}}} & \text{for } \dot{\gamma} \leqslant \dot{\gamma}_c \\ \eta_{\mathrm{II}}(\dot{\gamma}) = \eta_{\mathrm{max}} + \frac{\eta_c-\eta_{\mathrm{max}}}{1+[K_{\mathrm{II}}((\dot{\gamma}-\dot{\gamma}_c)/(\dot{\gamma}-\dot{\gamma}_{\mathrm{max}}))\dot{\gamma}]^{n_{\mathrm{II}}}} & \text{for } \dot{\gamma}_c < \dot{\gamma} \leqslant \dot{\gamma}_{\mathrm{max}} \\ \eta_{\mathrm{III}}(\dot{\gamma}) = \frac{\eta_{\mathrm{max}}}{1+[K_{\mathrm{III}}(\dot{\gamma}-\dot{\gamma}_{\mathrm{max}})]^{n_{\mathrm{III}}}} & \text{for } \dot{\gamma} \leqslant \dot{\gamma}_{\mathrm{max}} \end{cases} \tag{2}$$

where, $\eta_I, \eta_{II}, \eta_{III}$ are the viscosity functions that fit the zones of shear thinning, shear thickening, and shear thinning of the general viscosity curve. K_I, K_{II}, K_{III} possess time dimensions and are responsible for the transitions between the plateaus and the power-law; n_I, n_{II}, n_{III} are the dimensionless exponents related to the slopes of the power-law regimes; η_{max} and $\dot{\gamma}_{\mathrm{max}}$ are the maximum viscosity and the corresponding shear rate, respectively; $\dot{\gamma}_c$ and η_c are the critical shear rate and corresponding viscosity, respectively; they were obtained from the experimental data shown in Fig. 2.

The fitting curves agree with the experimental results, as shown in Fig. 5. The three typical regions of the rheological properties of the STF are situated in the fitting curves: slight shear thinning at a low shear rate, shear thickening over the critical shear rate, and obvious shear thinning at a high shear rate. And the values of the parameters in Eq. (2) are also presented in Table 2, which can be

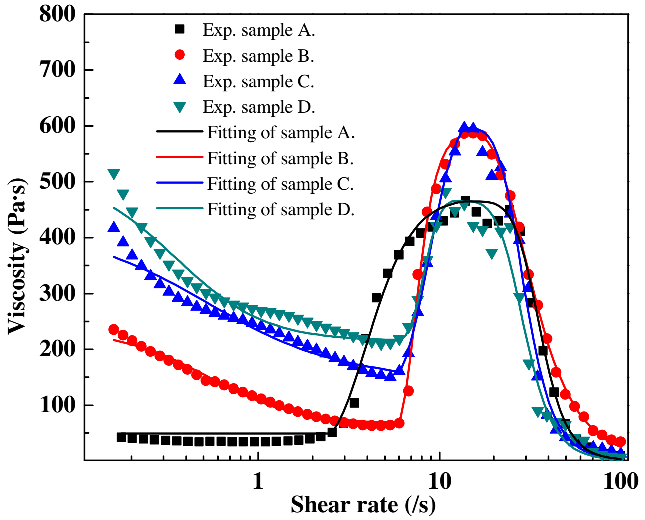

Fig. 5. The fitting curves and experimental results.

Table 2
Parameters in Eq. (2) for different samples obtained by fitting method.

	Pure STF	STF + 0.625% SiC Nanowires	STF + 0.975% SiC Nanowires	STF + 1.250% SiC Nanowires
K_I	−0.0036	−19.82	−22.11	−47.57
K_{II}	−1.15	−0.54	−0.19	−0.21
K_{III}	0.045	0.055	0.062	0.057
n_I	11.91	0.85	0.60	0.84
n_{II}	1.10	1.47	1.14	1.61
n_{III}	1.12	2.02	3.08	3.29
η_0	49.40	235	417	516
η_c	51.39	68.41	158.06	216.55
$\dot{\gamma}_c$	2.56	5.92	5.98	5.98
η_{max}	465	587	596	466
$\dot{\gamma}_{max}$	13.9	15.4	13.7	12.2

used to describe the curve of viscosity-shear rate of STF in the numerical calculations.

Conclusions

In this study, SiC nanowires were used to improve the properties of pure SiC/PEG400 STF. To investigate the effect of the SiC nanowires on the rheological behavior of the STF, three different types of STF with SiC nanowires were fabricated and characterized. The results showed that the SiC nanowires had a significant influence on the initial viscosity and the thickening behavior of STF. Combining the cluster theory, the mechanism of the STF with SiC nanowires was discussed. It indicated that adding SiC nanowires is a valid way of improving the rheological properties of STF.

A viscosity function model was used to fit the experimental results, and the fitting-curves agreed with the experimental results. Three typical regions of the viscosity curves were well-fitted and would therefore be useful if they were used in numerical simulation of the application of the STF for future work.

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