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Shear dependent electrical property of conductive shear thickening fluid

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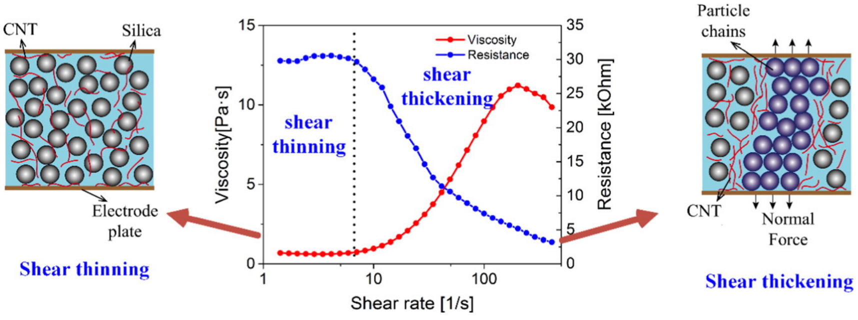
HIGHLIGHTS

- Carbon nanotube (CNT) particles enhance the shear thickening effect of conductive shear thickening fluid (C-STF).
- The C-STF possesses unique electrical property due to the presence of CNT.
- Resistance of C-STF critically decreases once accounting the unexpected shear and the decrements reached to as high as 90%.
- The shear dependent impedance spectroscopies can describe the structure evolution during the shear thickening procedure.

GRAPHICAL ABSTRACT



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ABSTRACT

Conductive shear thickening fluid (C-STF) consisting of SiO_2 particles, carbon nanotube (CNT) and ethyl glycol (EG) was developed. The shear thickening effect of C-STF was strengthened with the increasing CNT mass fraction. Different from the traditional shear thickening fluid (STF), the as-prepared C-STF showed unique electrical property due to presence of the conductive doping CNT. The initial resistance of C-STF varied from 94 kΩ to 18 kΩ at different CNT mass fractions (0.1 wt%, 0.2 wt%, 0.3 wt% and 0.4 wt%). Moreover, the resistance could be critically decreased once accounting the unexpected shear and the decrements reached to as high as 90%. Meanwhile, the shear dependent impedance spectroscopies at different shear rates were analyzed and an equivalent circuit model was proposed to investigate the microstructure dependent electrical property. This phenomenon not only gave much valuable information for understanding the detail shear thickening mechanism but also broadened their application in anti-impact sensor.

1. Introduction

Shear thickening, as a kind of non-Newtonian flow behavior, is widely existing in dense particle suspensions [1–6]. When the applied shear rate exceeds a critical value, viscosity of shear thickening fluid (STF) will increase dramatically. During the past decade, multiple theoretical and experimental methods have been adopted to investigate the origination of shear thickening phenomenon [7–10]. Usually, hydrocluster mechanism is used to illustrate the reversible shear thickening phenomenon in dense Brownian suspensions [1,5,6], while shear jamming is responsible for discontinuous shear thickening in dense non-Brownian suspensions. Dilatancy, which is a consequence of shear jamming, is due to a flow-induced volume expansion caused by frictional interactions between particles [11–21]. Because of the unique shear thickening behavior, the STF has been widely applied in soft armor, damper, liquid couplings, shock absorption, ballistic protection, and etc. [22,23].

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Since the responds of the mechanical behavior to the external stress is really quick, it is very difficult to in situ detect the state during the working time. It was claimed that the force network sustained by particle chains occurred during the shear thickening procedure. In this case, the contacts between particles played an important role in supporting the applied stress [3,22]. Electrical signal of materials, which can respond to external mechanical deformation and microstructure evolution, is appropriate to be used as a detection signature [24,25]. However, most of the research in STFs was focused on their rheological properties, the investigation of the shear dependent conductivity has not been reported. In consideration of that the ST behavior is highly dependent on the structure transformation of the inner-contacted dispersing particles, an electric-mechanical coupling property will be valuable for studying their shear thickening behavior.

Multi-walled carbon nanotubes (CNT), which show excellent mechanical properties, electrical conductivity and the characteristic of low density, are ideal nano-additives to reinforce and functionalize traditional materials [24–27]. Due to the incredible forms of strength and conductivity, CNT plays an important role in improving the performance of multifunctional materials in sensors, probes and electrochemical devices [28–30]. Because of the highly conductive network built by CNT, the CNT doped nano-composites demonstrated typical semi-conductive characteristics [31]. Recently, with the technique of current injection phase thermography, the incorporation of CNT provided a novel way to detect the impact damage in composite laminates [32]. Interestingly, the CNT was also effective for improving the rheological properties of the STF [33,34]. Sha et al. studied the influence of CNT on the shear thickening effect [35]. Because the net structure formed by CNT restricted the particle motions, the shear thickening phenomenon was accelerated [35–37]. Obviously, the homogeneously dispersed CNT within the SiO_2 based STF assembled to form unique conductive road thus presented the typical electrical conductive property. Unfortunately, the electrical property of the conductive STF has not been reported till now.

Electrical property includes direct current (DC) conductivity and alternating current (AC) conductivity. The DC conductivity was commonly used as a sensing signal while the AC conductivity can be developed as a new method to understand the structure evolution [31,38]. The AC conductivity is usually conducted by applying a sinusoidal electrical stimulus signal to an electrode-materials system during the Impedance Spectroscopy measurement [39–41]. By collecting the response signals, the electrical property of the measured materials and the interface behavior between the electrode and sample were obtained [42,43]. Equivalent circuit was usually used to conclude the evolution process in electrode-materials system [44]. Xu et al. studied the impedance responses of magnetorheological plastomers. It was found that equivalent circuit was useful in revealing the particles rearrangement induced by magnetic field [45]. Any intrinsic property that affected the conductivity of an electrode-materials system could be investigated by impedance spectroscopy [46]. As for C-STF, both rheological property and electrical property were sensitive to the chain-like aggregations of dispersed particles and doping. The resistance variation in C-STF during the shear thickening procedure can be collected as a signature to detect the working condition of STF in applications. In additionally, the impedance spectroscopy was useful in characterizing the particle distributions of STF. Therefore, developing a kind of C-STFs and investigating their shear dependent electrical property are necessary.

In this work, a novel conductive STF (C-STF) doped with CNT was developed. The as-prepared C-STF showed excellent shear thickening effect and special electrical property. Rheological experiments indicated that shear thickening effect of C-STF was enhanced with increasing the mass fraction of CNT. Meanwhile, the electrical property of C-STF was firstly investigated. Both the DC and AC conductivities were sensitive to the shear rate and could be easily adjusted by varying the mass fraction of CNT. In the shear thickening region, there was an obvious decrement in resistance with the increasing shear rate. The impedance spectroscopy at different shear rates was also compared. Equivalent circuit models were proposed to explain the structure dependent impedance.

Table 1
Compositions of C-STF samples.

Sample no.	Group 1					Group 2			
	1	2	3	4	5	1	6	7	8
SiO_2 mass fraction (%)	64	64	64	64	64	64	62	66	68
CNT mass fraction (%)	0.3	0	0.1	0.2	0.4	0.3	0.3	0.3	0.3

2. Experimental section

2.1. Preparation of C-STF

SiO_2 particles with an average diameter of 2 μm were obtained from industrial grinding. CNT with a length of 3–12 μm was purchased from Conductive Materials of Luelida Co. Ltd., Xinxiang, Henan province, China. The other analytical chemical reagent including ethylene glycol (EG), ethyl alcohol and acetone were purchased from Sinopharm Chemical Rea Co. The SiO_2 and CNT particles were pre-processed before used. Typically, different amounts of SiO_2, CNT and sodium dodecyl benzene sulfonate (SDBS) were homogeneously dispersed in a solvent consist of ethyl alcohol and acetone (1/1, v/v) by mechanical stirring (JJ-6, purchased from Jintan Jinnan Instrument Manufacture Co., Ltd., 300 r/min) for 2 h. SDBS is a kind of surfactants, effective for improving the dispersity of CNT particles. The weight ratio of CNT and SDBS was kept at 5:1 while the weight ratio of SiO_2 and CNT depended on the compositions of each sample. At last, the obtained particles were dried in a vacuum oven at 40 °C. The pre-processed procedure is used to form a uniform dispersion of SiO_2 and CNT particles in the solvent. Without the pre-processed procedure, there will be many bundles in CNT and then the shear thickening effect and conductivity of C-STF are both weakened [47].

The STFs were prepared by dispersing the processed SiO_2 particles and CNT into ethylene glycol. Sodium dodecyl sulfonate (SDS), a kind of anionic surfactants, was also added to the suspensions to strengthen the shear thickening effect [48]. Both dispersed phase and dispersed medium were mixed in a ball grinding mill (QM-3SP2, purchased from Nanjing NanDa Instrument Plant, 230 r/min) for 24 h to obtain uniform suspensions. In this work, two groups of C-STF were prepared and the compositions of all samples were shown in Table 1. Group 1 was the samples with different CNT mass fractions (0 wt%, 0.1 wt%, 0.2 wt%, 0.3 wt% and 0.4 wt%) while the mass fraction of SiO_2 was fixed at 64 wt%. Group 2 was the samples with different SiO_2 mass fractions (62 wt%, 64 wt%, 66 wt% and 68 wt%) while the mass fraction of CNT was fixed at 0.3 wt%. The samples were numbered from sample 1 to sample 8.

2.2. Rheological measurements

The experiments were performed primarily in a stress and strain controlled rheometer (Anton-Paar MCR 301). The CP25-2 and the CC-10 were both used as test accessories to investigate the rheological property of C-STF. CP25-2 is a cone-plate accessory with a cone angle of 2° and a diameter of 25 mm. CC-10 is concentric cylinders. For steady shear tests, an equilibration time of 60 s was given at the beginning to allow the system to reach steady shear. All the rheological measurements were conducted at room temperature of 25 °C.

2.3. Electrical test system

The electrical test system was built by connecting the rheometer with a Moudulab material test system (MTS, Solartron analytical, AMETEK advanced measurement technology, Inc., United Kingdom)