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Electrorheology of Diamond/PDMS Nanofluids in Steady and Oscillatory Shear

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Abstract:
The rheological properties of diamond (< 10 nm) in silicone oil (PDMS) were analyzed using steady shear and oscillatory shear measurements. Unlike micron sized diamond suspensions these suspensions were non Newtonian and showed strong viscoelastic behavior without the electric field applied. Furthermore these nanodiamond mixtures showed sigmoidal behavior for their apparent viscosity as the shear rate is increased without the electric field applied. When the electric field was applied the apparent viscosity of the mixtures increased by an order of magnitude at lower shear rates. The effects of electric field and concentration on diamond rheology are both examined. The rate of shear thinning for the mixtures is high when the applied electric field is high. At high shear rates for the mixture the electric field does not have much effect. The flow curve was described by the Herschel-Bulkley model. Yield stress values obtained from the model gives an important relationship between yield stress, electric field and concentration, that is $\tau \propto E^n$ and where $0.8 < n < 1.3$.

Key words:
electrorheology, carbon, diamond, nano powder, yield stress, electrorheological fluid

1 INTRODUCTION

Carbon nanoparticles have been shown to enhance the properties and performance of suspensions, composite blends, and gels. While several forms of carbon exist, diamond is unique because it is highly insulating both electrically and thermally [1]. The insulating properties of diamond contrast with the semiconducting forms of carbon including carbon multiwall and single-wall nanotubes, fullerenes, and graphite. For diamond it is the arrangement of the atoms in the carbon solid that affects the electrical transport and the particle-particle interactions within the fluid. Previous research already indicates that these semiconducting forms of nanoparticles significantly increase the viscosity and yield stress of suspensions both with and without the application of electric fields [2–4]. This paper examines the rheological behavior of nanodiamond in an insulating oil with the application of the electric field.

For the nanodiamond suspensions it is important to define both nanofluids and electrorheological fluids. First, not all carbon nanoparticles placed in insulating fluids are considered "nanofluids". For carbon nanoparticle suspensions, such as the mixtures of nanodiamond/PDMS, to be considered a "nanofluid" and be used in nanofluid applications certain requirements must be met. The requirements for a typical nanofluid include low solids concentration, great stability, and favourable flow behavior [5]. Second, for a suspension to be considered an electrorheological fluid it must show a strong increase in the apparent viscosity upon the application of an electric field, and the viscosity should return to the original value when the electric field is removed. A notable case where the reversibility condition was not met was the "nanofluid" made of carbon nanoparticles of fullerenes in PDMS, which lacked reversibility but did show an increase in upon the application of the electric field [3]. Thus the requirements for conventional ER fluids are favourable flow behavior, great stability, and reversible increases in viscosity upon the application of the electric field.

For a mixture to be both a nanofluid and an electrorheological (ER) fluid the suspension should have favourable flow behavior, great stability, low solids concentration, and a reversible increase in viscosity upon the application of the electric field. The favourable flow requirement and low solids concentrations exclude many systems that qualify as ER fluids from being nanofluids. ER Fluids containing nanosized particles but at high concentrations that have shown strong vis-

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havior seen for ER fluids under an electric field in Figure 8. Other systems that show similar characteristics include: xantham gum solutions surfactant solutions and biopolymer solutions [25].

Based upon this data and the apparent yield stress that develops within the nanoparticles of diamond and silicone oil system it can be concluded that the system is that of a gel. The loss modulus and the storage modulus both increased with increasing concentration of diamond nanoparticles within the mixture. Even at 1 % diamond concentration the rise in the loss modulus is significant. The PDMS without diamond shows none of these effects. The storage modulus for the diamond nanoparticle suspension under the electric field increases with both electric field and concentration. The loss modulus also is seen to increase with the electric field and concentration. The critical strain, where G' and G'' cross, for the different electric fields is also shown in Table 3. It is noted that the critical strain varied with concentration and electric field showing no apparent trend. During the experiment shown in Figure 9 the electric field is increased from 0 to 4 kV/mm. We observe that the value of storage modulus goes up with increase in electric field indicates the chain formation in the suspension and is becoming stronger under electric field [26]. For larger particles only the volume fraction determines the contribution of the particles. But it's different when it comes to the smaller particles. Nanoparticles can contribute to the frequency dependent storage modulus by Brownian motion [27].

4 CONCLUSION

Rheological and Electrorheological properties of nanodiamond in silicone oil suspensions have been analyzed and discussed in this paper. These suspensions show shear thinning behavior in the absence of an electric field. With the application of an electric field the shear stress values for nanodiamond suspension goes up by the order of 10. The dependence of the observed ER response on field strength shows a near linear dependence on the field strength. The experimental data shows the yield stress dependence on electric field $\tau_y \propto E^n$ where n is in between 0.8 to 1.28 for electric field range of 1 to 4 kV/mm. The viscoelastic analysis of ER suspension shows strain thinning behavior. The storage and loss modulus increased with increasing concentration for the diamond suspension. The viscoelastic analysis of the ER suspension also shows the storage and loss modulus increase by increasing the applied electric field. The viscoelastic analysis suggests that both the formation and strength of the nanodiamond structures in PDMS are enhanced by increasing the magnitude of the electric field.

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