Original Contributions

Director dynamics of uniformly aligned nematic liquid crystals in transient shear flow

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Abstract: We have developed a modular rheo-optical apparatus to study the flow properties of liquid crystals. Its main components are shearing device, strong magnetic field, and optical microscope. We performed experiments on well-defined initial morphologies with uniform molecular alignment. The monodomains were achieved with strong magnetic fields (4.7 T). Time-resolved conoscopically is the primary optical technique in our investigation. We propose a simple relation between the distribution of alignment angles over the sample thickness and the conoscopically measured angle, to quantitatively measure the alignment angle in shear flow.

We followed the relaxation of a shear-induced splay deformation in small molecule model systems (N-(p-methoxybenzylidene)-p-butylaniline (MBBA), pentyl-cyano-biphenyl (5CB) and a commercially available mixture OMI4244). We define a rotational director diffusivity \( D_R = \frac{K_s}{\eta_s} \) (\( K_s \) splay elastic constant, \( \eta_s \) splay viscosity) from the relaxation process and devised a model, based on the diffusion equation to determine their values.

The director alignment behavior of the small molecule liquid crystals (SMLC's) in shear flow is well described by the two-dimensional Leslie-Ericksen model. The effect of director elasticity can clearly be seen in our experiments, resulting in a decrease of the steady state alignment angle at smaller Ericksen numbers.

We found that there is no strain rate dependence of the director vorticity from 0.002/s to 2/s for poly-(y-benzyl-D/L-glutamate) (PBG). We determined \( \alpha_s/\alpha_3 = -44 \) for a 20% solution of 280000 molecular weight PBG in m-cresol at 20°C. The conoscopic interference pattern vanished after 8 strain units from an initially planar alignment and shearing could be reversed up to 10 strain units to completely recover the initial monodomain.

Key words: Liquid crystal – monodomain – conoscopically – Leslie angle – flow alignment – director diffusion

1. Introduction

A number of studies in recent years have been aimed at a better understanding of the complex balance between external fields (shear-, magnetic-, electric field) and molecular orientation of polymeric liquid crystals. Conventional rheological techniques for the characterization of the flow behavior have been complemented with optical measurements, namely small angle light scattering, polarized light microscopy, birefringence measurements, and conoscopically.

Conoscopic has been successfully used by Cladis (1972) and Pieranski and Guyon (1973, 1974) to study alignment behavior of small molecule liquid crystals. More recently Berry and Srinivasarao (1991) applied this technique to monodomains of poly(benzobisthiazole) (PBT). Liquid crystalline materials may be characterized with respect to their flow aligning behavior. They found that the material is non flow aligning in shear flow. In general, most polymeric nematogens exhibit non flow aligning behavior. How-
ever, recently it has been shown for a semiflexible thermotropic LCP by Srinivasarao et al. (1992) that flow alignment may strongly depend on temperature. They found that the director is flow aligning when close to the nematic-isotropic transition and non flow aligning when close to the smectic-nematic transition. They interpreted their findings in terms of a sign change of one of the Leslie viscosity coefficients.

Burghardt and co-workers (1991, 1993a, b) correlated birefringence measurements with the degree of molecular orientation for textured solutions of poly(benzyl glutamate). They found a correlation between the transition zone of a low plateau and high plateau birefringence and the first normal stress difference for steady state shear.

Yang and Shine (1993) studied the stress response of uniformly aligned poly(hexyl isocyanate) and interpreted their experimental findings in the framework of the TIF (transversely isotropic fluid) model by Ericksen (1960). They were able to determine some of the Leslie viscosity coefficients.

Larson et al. (1993) recently characterized textured solutions of poly(benzyl glutamate) using polarized optical microscopy. He interpreted his experimental findings in the framework of the Ericksen number and Deborah number and observed that PBG becomes flow aligning at high Ericksen numbers, which has been predicted by molecular theory (Larson et al. 1990, 1992).

A molecular theory was first suggested by Hess (1975a, b, 1976) and has been further developed by Kuzuu and Doi (1983, 1984), Marrucci (1982, 1985) and Larson (1990) to describe the flow behavior. It is capable of predicting a region with negative first normal stress difference which has been observed earlier for solutions of poly(benzyl glutamate) by Kiss and Porter (1978, 1980).

A continuum theory for flow behavior of mesophases has been developed by Ericksen and Leslie (1960, 1962, 1966). It requires six viscosity coefficients, five of which are independent due to Parodi's (1970) relation, and three elastic constants to describe flow of a uniaxial liquid crystal. However, the theory is tailored to describe the rheological behavior of uniformly aligned nematogens, so called "monodomains", and, hence, does not account for formation and evolution of defects and texture.

This study intends to quantify the shear effects on initially uniform alignment LC fluids, and to measure the dominant material parameter. For that purpose, we built a shearing device integrated in an optical microscope and observed the effect of shear on uniformly aligned nematic liquid crystals, both small molecule and polymeric LC's. Monodomains serve as well defined initial condition for our flow experiments. Time-resolved conoscopic measurements give the tilt and twist motion of the director as a function of imposed strain and our findings are interpreted in the framework of director diffusion and the Leslie-Ericksen theory.

2. Experimental methods

2.1 Rheo-optical apparatus

Shearing device. The shearing device for simultaneous optical and rheological measurements is integrated in an optical microscope (Zeiss Universal Stand) which can be operated in conoscopic and orthoscopic mode. A schematic of the device is given in Fig. 1. The shearing unit is mounted on a base plate which is attached to the microscope stage. It can be easily detached and placed on an optical tray inside the bore of a superconducting magnet. All parts are exclusively manufactured from brass or stainless steel and allow the device to be operated in strong magnetic fields.

The lower plate is driven by an inchworm motor (Burleigh Inc.) with respect to a stationary upper plate. The linear piezo motor allows speeds in the range from below 0.1 μm/s up to 2 mm/s. Total displacement is measured by an optical encoder. A dove tail sled provides very precise and smooth motion of the moving plate.

The sample is confined between two rectangular glass slides, 25 mm x 75 mm, which are mounted in the shearing device. Spacers (Kapton sheet, glass) be-