Tribology International 94 (2016) 20–25

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Measurement of lubricant viscosity and detection of boundary slip at high shear rates

Xiang Yu [a], Yonggang Meng [a,*], Yu Tian [a], Jun Zhang [a], Weibin Liang [b]

[a] State Key Laboratory of Tribology, Tsinghua University, Beijing 100084, China
[b] Department of Precision Instrument, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 9 May 2015
Received in revised form
22 July 2015
Accepted 6 August 2015
Available online 14 August 2015

Keywords:
Viscosity
Boundary slip
Ultra shear rheometer
Friction reduction

ABSTRACT

A novel rheometer with the maximum shear rate of $10^5\ s^{-1}$ has been fabricated to measure lubricant viscosity and to detect solid/liquid boundary slip. The gap between two parallel plates is controlled in the range from 20 to 500 μm and the viscous shear torque is measured with a feed-backed laser reflection technique. Test results of the perfluoropolyethers (PFPE) coated sample indicated that the viscous shear resistance is reduced by about 15–20% compared with the bare plate, implying that possible boundary slip occurred at the liquid/solid interface and a slip length of order 10 μm was extrapolated.

1. Introduction

Friction between solid and liquid interfaces plays an important role in many mechanical devices such as high speed bearings and liquid-floated gyroscopes. The interfacial friction depends greatly on rheological behaviors of liquids and interactions at high shear rates, which are not well understood fundamentally. There are a lot of demands to fully elucidate the precise nature of the rheological and interfacial performance of liquids at high shear rates despite many seemingly classical theories at low shear rates. Some Newtonian liquids such as ethylene glycol and glycerol were found to exhibit different rheological responses significantly at high shear rates [1].

The most critical issue to achieve high shear rates is to obtain good alignment of the shearing plates and steady flow of the sheared liquids. Measurement of viscosity using cylindrical Couette device, capillary rheometer and rotating plates were done at high shear rates with limited shear rates [2–5]. Rotational rheometers were widely used to study the rheological and interfacial properties due to their easy cleaning and variable gap.

Liquids were found to exhibit non-Newtonian behaviors at high shear rates, such as shear thinning [6,7]. Experiments done by Ram showed that Newtonian liquids might exhibit shear thinning when the shear rate exceeded $60{,}000\ s^{-1}$. But later experiments found that the decreased viscosity of glycerol was caused by viscous heating and the viscosity was constant up to $90{,}000\ s^{-1}$ [1]. With good control of the shear pulse duration, Feng et al. found that the lubricants were observed to be rate-sensitive over the entire range of shear rates examined and softening was observed at high shear rates [8]. Kavehpour and McKinley found that the triborheological properties of three common gear lubricants with similar viscosities were quite distinct in the transition to the mixed lubrication regime [9].

Friction between solid surface and liquids was mainly studied with instruments such as surface force apparatus (SFA) and quartz crystal microbalance (QCM) [10]. Molecular dynamics (MD) simulation was also used to analyze friction theoretically [11]. Many results of friction were related to another phenomenon, known as boundary slip. No-slip boundary condition was effective at macro-scale system, but could not be acceptable at micro and nano-scales. Navier [12] first proposed the theory of boundary slip which was accepted in recent years [13,14]. Slip length was frequently used to quantify the extent of boundary and varied from less than 1 nanometer to several micrometers. Boundary slip tended to happen on hydrophobic surfaces [15,16] and there was a critical shear rate for slip [17].

Till now, most researches on rheology mainly concentrate on the rheological behavior while researchers of interfaces mostly focus on the interfacial behavior at the liquid/solid interfaces. In fact, rheological response of liquids and solid/liquid boundary interactions are tightly interlinked. The two research interests should be studied with one apparatus and coupling effect should be considered. Therefore, a novel rheometer with variable gap and plates could be very helpful to investigate the solid/liquid

* Corresponding author. Tel.: +86 10 62773867.
E-mail address: mengyg@tsinghua.edu.cn (Y. Meng).

http://dx.doi.org/10.1016/j.triboint.2015.08.005
0301-679X/

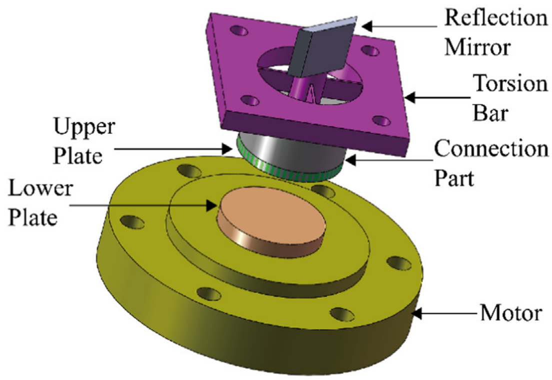

Fig. 1. Schematic diagram of ultra shear rheometer.

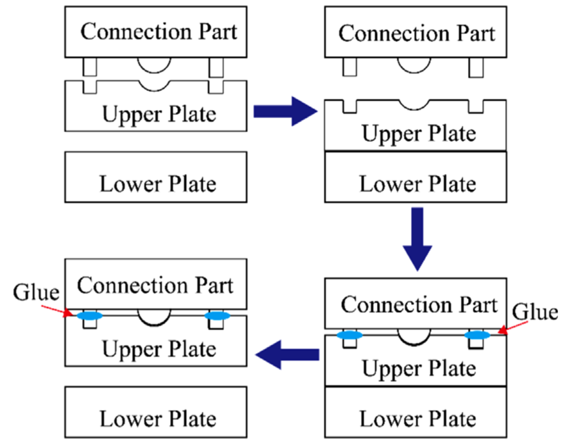

Fig. 2. Schematic of fixation. Firstly, the upper plate is put on the lower plate to keep them parallel. Then the connection part comes into contact with the upper plate and some glue is added between them. Finally, the connection part and upper plate are lifted up after the glue is dried.

interfacial interactions as well as rheological response at high shear rates. In present study, a novel ultra shear rheometer with high speed and shear rates was developed to study the friction and boundary sip. Liquids including deionized water, propylene carbonate (PC) and 3 # mineral oil were used to analyze their behavior on viscosity and friction reduction. Surfaces of bare stainless steel and coated with PFPE were used to investigate the effect on boundary slip. Results showed that liquids exhibited shear thinning and surfaces coated with PFPE could reduce solid/liquid interfacial friction by 15–20%. Boundary slip might happen in the interface between solid and liquids and a slip length of order 10 μm was extrapolated.

2. Experiments

2.1. Apparatus

A novel ultra shear rheometer was built in order to evaluate the properties of boundary slip and friction between solid-liquid interfaces with a gap width from 20 μm to 500 μm at high shear rates. It has two parallel plates with a diameter of 20 mm. The lower plate is attached to an air bearing spindle and the upper plate is connected to a torsion bar which allows limited rotating angle about the vertical axis. The schematic diagram is shown in Fig. 1.

The upper sample is connected to the torsion bar via a connection part which can keep the plates be parallel during testing. The schematic diagram of the fixation process is shown in Fig. 2. The mechanism involves a ball-joint with pins which allow a limited rotation for the upper plate. Firstly, the upper plate and connection part is put on the lower plate and let the two plates come into contact. Then the connection part is put down and contact with the upper plate which will keep the two plates parallel. Thirdly, some glue is added to the pins and corresponding holes. Finally the upper platform is lifted up after the glue is dried.

As shown in Fig. 1, during testing, the lower plate is rotating and a resulting torque is exerted on the center of the torsion bar via shear stress between the plates. Then a limited rotation angle which is proportional to the resulting torque is generated in the center of the torsion bar with the deflection of the web plates in the torsion bar. A reflection mirror is mounted on the center of the torsion bar. The angular distortion of the torsion bar under shear is measured with a laser reflection method and the optical path is lengthened by several reflection mirrors to achieve better sensitivity. There is a negative feedback loop between the detector and a piezo actuator mounted behind one of the reflection mirrors to enlarge the measuring range and increase the stability of the laser spot on the detector. The voltage applied on the piezo actuator can be detected and the torque is calibrated with respect to the voltage. The laser path is shown in Fig. 3. A high speed camera is used to capture the images of the plates and inner liquid.

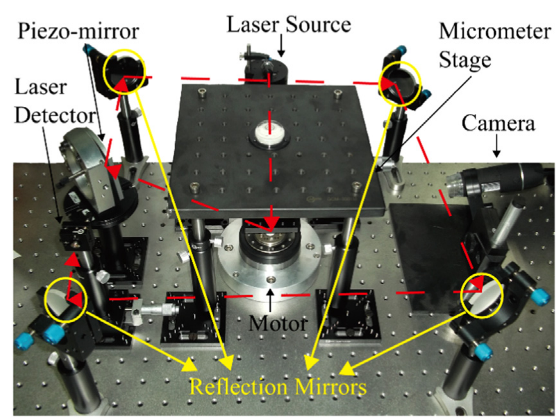

Fig. 3. Photograph of ultra shear rheometer with the laser path highlighted with dashed red lines.

The upper plate and the torsion bar are attached to a precise micrometer stage. The stage consists of one manual lifting platform and one piezo platform. The manual platform can be lifted in the range of 25 mm with a resolution is of 1 μm. The piezo platform has a range of 120 μm and the resolution is 10 nm. Two eddy current sensors (DT3010-A-U05, Micro-Epsilon, Germany) are placed on both sides of the stage to detect the displacement on average. The eddy current sensors have a range of 500 μm and the resolution is 40 nm. The combination of the manual and piezo platform makes it precise enough for the positioning with sufficient rigidity. A negative feedback loop is designed between the piezo platform and the eddy current sensors to keep the platform at the right position during testing.

An air bearing spindle (S/N 78091, Seagull Solutions Inc, USA) is used to drive the lower plate. The motor has a maximum speed of 15,000 rpm. Dynamic balancing is adjusted before testing. The lower plate is adjusted to be perpendicular to the spindle with laser doppler velocimetry (OFV-534/5000, Polytec GmbH, Germany). The lower plate may tilt when the motor is rotating and this phenomenon will generate errors during testing. The runout of the lower specimen during rotation was measured with a laser doppler velocimetry (LDV, Polytech, OFV-534). Through a precise adjustment of the lower plate, the largest axial runout was lower than 1.8 μm. The displacement and torque data is collected by a