Rheology meets tribology: updated Stribeck curve for the lubrication between smooth surfaces

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The Stribeck curve is a fundamental concept to characterize the shear behavior in the entire range of lubrication, including hydrodynamic, mixed, and boundary lubrication regimes [1]. The Stribeck curve represents friction force F (friction coefficient μ) as a function of the Hersey number (= $\eta V/L$) that governs the lubricant oil thickness D, where η is the viscosity of lubricant oil, V is the sliding velocity, and L is the applied load. This concept includes both rheology (flow of lubricant liquid in the hydrodynamic lubrication regime) and tribology (contact between surface asperities and slid in the boundary regime) and is widely used to grasp the shear behavior in practical sliding systems. However, there are at least two major problems from the quantitative viewpoints:

i) The Hersey number assumes that the effect of increasing V and decreasing L on D (and resulting F) is quantitatively equivalent, which is baseless.

ii) The oil viscosity η is regarded as constant, but decades of researches have revealed the dramatic increase of η in confined geometries [2].

The difficulty to solve these problems comes from the fact that most of the friction measurements only detect F under given L and the essential parameter D during sliding is unknown. The surface forces apparatus (SFA) is eminently suitable to approach this issue because SFA enables the direct measurement of D using optical technique called fringes of equal chromatic order (FECO) simultaneously with the friction measurement. The SFA uses molecularly-smooth mica as substrate, and the real contact area A is also obtained by the FECO technique. This means that the viscosity (referred to as "effective viscosity η_{eff}") of molecularly-confined lubricant in the boundary lubrication regime can be directly evaluated using the Couette flow equation:

$$\eta_{\mathrm{eff}} = FV / AD. \qquad (1)$$

By using η_{eff} as a quantitative parameter, attempt was made to bridge the gap between rheology and tribology and quantitatively "update" the Stribeck curve for the lubrication between smooth surfaces. Israelachvili and his coworkers [3,4] measured the shear behavior of a polymeric lubricant as a function of V and D, and proposed a new diagram to describe the V dependence of F and η_{eff}. The measured F in the low V region (boundary regime) is much larger than that in the high V region (hydrodynamic regime) like that in the "conventional" Stribeck curve. However, the physical origin of the F increase was not the direct contact between surface asperities but by the viscosity increase of intervening lubricant liquid. The viscosity increase is interpreted as a glasslike transition induced by confinement [5], and the WLF (Williams-Landel-Ferry) like superposition principle was applicable to the viscosity behavior against lubricant thickness. Experimentally attainable V range was not wide enough to draw a whole picture, and computer simulation by Robbins et al. greatly improved our understanding of the overall dynamics [6,7]. Yamada proposed the existence of a universal viscosity curve in the shear thinning regime for the glasslike hard-wall lubricant liquids [8]; part of which was supported by the later numerical analysis by Persson [9].

Recently, water-based lubrication for soft interfaces has been received considerable attention. Extremely low μ ($\leq 10^{-3}$) in the boundary lubrication regime is often observed [10-12], which is explained from the high fluidity of water molecules even in molecular-scale confinement. The Stribeck curve for such systems is very different from that of oil-based lubrication systems, which will be also discussed.

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