

# Achieving Superlubricity under Boundary Lubrication

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Here we show that liquid superlubricity under boundary conditions (friction coefficients  $< 0.01$ ) can be easily obtained by coupling selected substrates (H-free DLC, Si-based ceramics) and green lubricants (vegetable oils, polyols, unsaturated fatty acids, etc.). Even, PAO base oil gives friction coefficients below 0.05. in all cases. Superlubricity is obtained with very low wear rates and formation of thin tribofilms is necessary. Tribochemical reactions take place at the beginning of the test and synthesize 2D- materials in the contact area (graphene, carbon nitride, metal hydroxides, etc.). H-bond networks separate the surfaces and cooperate to lower friction.

**Keywords:** superlubricity, boundary lubrication, unsaturated fatty acids, ceramic, H-free DLC.

## 1. Introduction

Liquid superlubricity under boundary lubrication (BL) can be defined by the occurrence of extremely low friction coefficients (below 0.01) under contact pressures above 300 MPa in a wide range of temperature and is associated with lambda values well below unity. Wear is also very low so that boundary lubrication regime is kept till the end of the friction test. At the opposite of structural superlubricity, frictionless sliding is not expected under liquid superlubricity. Importantly, measuring friction coefficient below 0.01 with a tribometer working at macro-scale is not straightforward and should be carefully argued. In these conditions, the number of lubricant molecules entering the contact zone is very limited (theoretical film thickness calculated of the order of molecular size) so that fluid flow and viscosity effects are not expected. More importantly, complex tribochemical reactions take place under the combined effects of pressure and shear creating new interface materials (tribofilms) and new surface terminations, playing a role in reaching superlubricity.

## 2. Methods

Liquid superlubricity using steel and a-C:H coatings combinations is very difficult to reach although not impossible (in this case, generally not lasting a long time). The situation is much favorable when using H-free DLC coatings and/or Si-based ceramic materials (SiC and Si<sub>3</sub>N<sub>4</sub>, etc.) associated with green lubricants like glycerol, vegetable oils (esters of polyols), unsaturated fatty acids and water-based systems. Symmetric pairs can be used but steel/DLC or steel/ceramic asymmetric pairs can also work very well.

The identification of triboreaction products created in the interface (responsible of superlow friction under BL) needs the use of specific techniques, combining surface analyses (XPS/AES/SIMS) and analytical FIB-EFTEM. Moreover, computer simulation is perfectly well adapted to the situation.

## 3. Results

Different examples showing liquid superlubricity under boundary lubrication are

investigated (see some examples table1). Even when lubricated by a pure PAO base oil, friction and wear are ultralow.

|                                         | castor oil | ricinoleic acid | oleic acid | linoleic acid | PAO 6 |
|-----------------------------------------|------------|-----------------|------------|---------------|-------|
| steel/a-C (30)                          | 0.004      | 0.009           | 0.015      | 0.06          | 0.04  |
| a-C (30)/Si <sub>3</sub> N <sub>4</sub> | 0.005      | 0.008           | 0.012      | /             | 0.04  |
| steel/Si <sub>3</sub> N <sub>4</sub>    | 0.04       | 0.006           | 0.02       | 0.05          | /     |

Table 1: friction coefficients of selected tribopairs lubricated by unsaturated fatty acids and castor oil. Contact pressure 300 MPa, temperature 80 °C, sliding speed 3 mm/s, lambda  $\ll$  0.1.

## 4. Discussion

Three mechanisms have been identified which are not exclusive: (i) *in situ* synthesis of lamellar compounds (graphene, carbon nitride, metal hydroxides, etc.) [1], (ii) hydrogen-bond network interface coupled with H/OH terminations and water nanofilm [2] and (iii) oligomerization of carbon surfaces [3, 4].

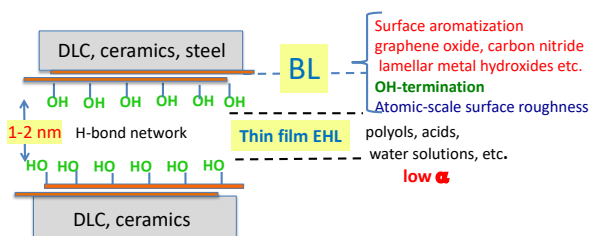


Figure 1: schematic picture showing a hybrid mechanism to achieve superlubricity both under BL and thin film EHL.

## 5. References

- [1] [1] Y. Long *et al*, **ACS Applied Nano Materials**, 4 (3) 2721 (2021).
- [2] [2] Y. Long *et al*, **Scientific Report**, 9 (1) 1-13 (2019).
- [3] [3] T. Kuwahara *et al*, **Coatings**, 11 (9) (2021).
- [4] [4] Y. Long *et al*, **Trib. Int.**, (169) 107 (2022).