

Chirality-Dependent Friction of Bulk Molecular Solids

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ABSTRACT: We show that the solid–solid friction between bulk chiral molecular solids can depend on the relative chirality of the two materials. In menthol and 1-phenyl-1-butanol, heterochiral friction is smaller than homochiral friction, while in ibuprofen, heterochiral friction is larger. Chiral asymmetries in the coefficient of sliding friction vary with temperature and can be as large as 30%. In the three compounds tested, the sign of the difference between heterochiral and homochiral friction correlated with the sign of the difference in melting point between racemate (compound or conglomerate) and pure enantiomer. Menthol and ibuprofen each form a stable racemic compound, while 1-phenyl-1-butanol forms a racemic conglomerate. Thus, a difference between heterochiral and homochiral friction does not require the formation of a stable interfacial racemic compound. Measurements of chirality-dependent friction provide a unique means to distinguish the role of short-range intermolecular forces from all other sources of dissipation in the friction of bulk molecular solids.



INTRODUCTION

Noncovalent intermolecular forces depend on the relative chirality of the interacting species. This fact leads to chirality dependence in surface adsorption,^{1–4} solubility,¹ and wetting.⁵ These thermal equilibrium properties are readily explained within the context of chirality-dependent free energies of interaction. For instance, in species where the racemate has a lower melting temperature than the pure compound, the racemate also tends to have a higher solubility^{6,7}—both effects arising from weaker heterochiral than homochiral interactions in the solid state.⁸

Chirality may also influence interactions out of thermal equilibrium, but these effects are difficult to predict or to simulate. Symmetry permits the friction of two solid surfaces to depend on the chirality of the interacting materials, though as a nonequilibrium process, the magnitude of this effect is hard to predict. We define the chirality-dependent component of the friction as $\Delta\mu \equiv \mu_{\text{hetero}} - \mu_{\text{homo}}$, where μ_{homo} is the coefficient of sliding friction between two surfaces of the same chirality and μ_{het} is the coefficient of sliding friction between surfaces of opposite chiralities.

In experiments on molecularly flat self-assembled monolayers, chemical force microscopy revealed chirality-dependent friction between a functionalized tip and a functionalized surface.^{9–11} In these experiments, the molecules were covalently immobilized and oriented. Thus, the friction was dominated by surface molecular interactions.¹² It was unclear, however, whether this asymmetry would survive in amorphous or polycrystalline surface interactions.

How significant are chiral forces in the friction of bulk amorphous or polycrystalline molecular solids? Solid–solid friction arises from a combination of intermolecular bonding interactions, long-range electrostatic forces, abrasion, surface roughness, and plastic deformation in the contacting materials.¹³ At finite humidity, water droplets nucleated near contact points may also contribute to friction.¹⁴ Furthermore,

the normal and shear stresses in the interaction of real solid bodies are typically highly nonuniform along the interface.¹⁵ In friction of bulk materials, molecules may reorient or even rearrange. One might expect all these effects to diminish chirality-selective friction, possibly to an undetectable level.

On the other hand, molecular-scale mixing across the interface might lead to formation of interfacial phases with different tribology and yield stress than the bulk materials. Most chiral molecules can form a stable racemic compound in which the two enantiomers pack in a 1:1 stoichiometry.¹ This compound has, in general, different thermodynamic and tribological properties from the pure enantiomers. Formation of a racemic compound manifests as a local maximum in the melting temperature at 1:1 stoichiometry in the binary phase diagram. The racemic compound can melt at a temperature either higher or lower than the pure enantiomers.

Other chiral species only form crystals of a single enantiomer and in an equimolar mixture form a conglomerate of intermixed enantiomerically pure crystallites. The equimolar conglomerate always melts at a lower temperature than the pure enantiomer. Friction between chiral surfaces incapable of forming a racemic compound could nonetheless be influenced by chirality-specific adhesive interactions between the crystallites comprising the two surfaces.

Thus, we studied three types of friction: (1) between species that form a racemic compound with melting temperature lower than that of the pure enantiomer, (2) between species that form a racemic compound with melting temperature higher than that of the pure enantiomer, and (3) between species that do not form a racemic compound. We tested one example of each scenario. All three showed chirality selectivity in friction, with fractional differences up to 30%. For the three compounds

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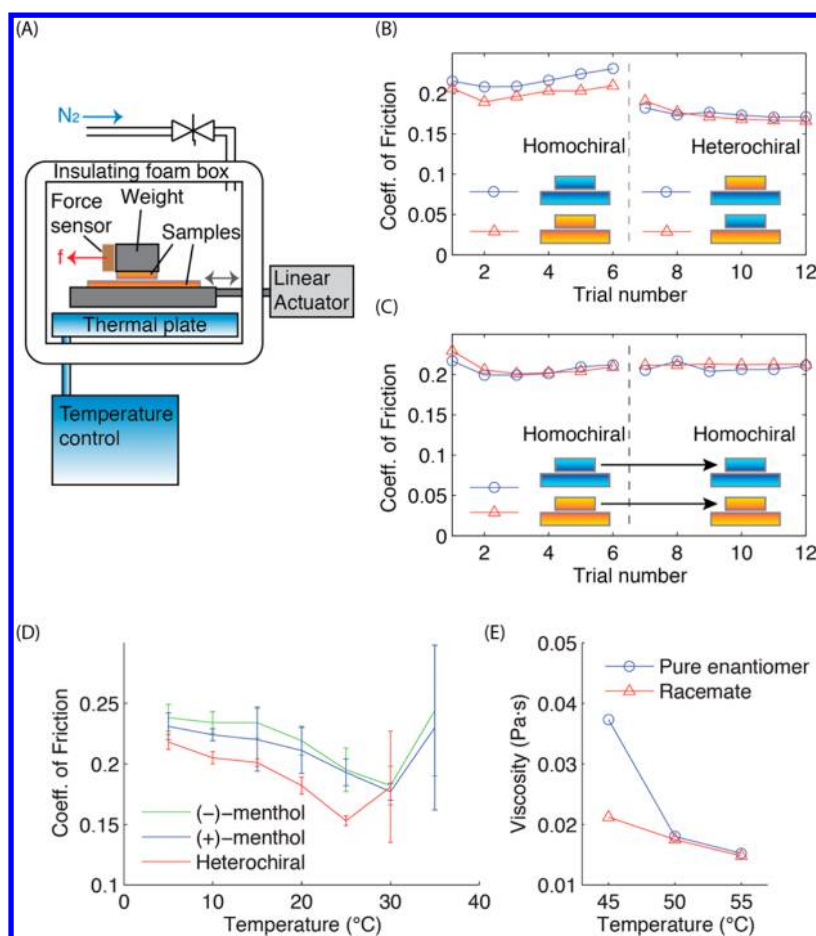


Figure 1. Menthol shows chirality selective bulk friction. (A) Experimental apparatus. Shear stress was measured under constant normal stress for homo- and heterochiral interfaces composed of polycrystalline bulk molecular solids. Temperature was held at 22 °C and relative humidity at 57%. (B) Repeated measurements of homochiral friction, followed by heterochiral friction on the same samples. (C) To test whether abrasive wear led to changes in the coefficient of friction, measurements of homochiral friction were followed by another set of measurements of homochiral friction. (D) Solid–solid friction at a normal stress of 8.7 kPa (112.3 g over 1.27 cm²) shows increasing fractional and absolute asymmetry in the friction coefficient as the melting temperature of the racemate is approached from below. (E) Viscosity of the pure enantiomer becomes greater than viscosity of the racemic mixture as the melting temperature of the pure enantiomer is approached from above.

tested, the sign of $\Delta\mu$ correlated with the relative melting points of the pure enantiomer and the racemic mixture, regardless of whether the racemate formed a compound or a conglomerate. While our results do not guarantee that this trend will hold for all chiral species, they establish the possibility of chirality-selective friction for any chiral molecular solid.

CHIRAL FRICTION OF MENTHOL

We sought to study the friction of amorphous or polycrystalline pellets of molecular solids. Candidate materials were selected where the melting temperatures of the racemate and single enantiomer were both near room temperature but were as dissimilar as possible. Many such melting points have been tabulated.¹ We speculated that the process of fracture at the interface could, on the molecular level, be similar to melting, and thus there might be a correlation between asymmetry in friction (between homo- and heterochiral interfaces) and asymmetry in melting temperature (between pure enantiomer and racemate).

The binary phase diagram of (+)- and (-)-menthol has been studied in detail.¹⁶ The pure enantiomer melts at $T_e = 42.9$ °C. The racemate forms a binary compound which melts at $T_r =$

33.8 °C. The experimental apparatus is shown in Figure 1a. Optically smooth films were formed by placing ~30 mg of menthol on an Al substrate and heating on a hot plate to 60 °C. A clean glass slide, coated with a self-assembled monolayer of trichloro(1*H*,1*H*,2*H*,2*H*-perfluorooctyl)silane (to prevent menthol adhesion), was then carefully lowered onto the molten menthol drop. The thickness of the menthol film was set to 50 μm by precisely machined aluminum spacers. The assembly was then transferred from the hot plate to a 4 °C refrigerator where it was allowed to cool for 10 min. The glass slide was then removed.

The top Al substrate comprised a puck-type scanning electron microscopy mount, 12.7 mm diameter (SPI 1506P-BA). The bottom substrate comprised a machined block of aluminum, 12.7 mm wide and 50.8 mm long. These were mounted in a custom apparatus for testing sliding friction. A calibrated weight placed on top of the puck maintained constant mean pressure at the interface. A force sensor (Futek LBB200) kept the top sample immobile and reported the interfacial shear stress, while the bottom sample was translated at constant velocity of 4.0 mm/s by a linear actuator (Zaber T-LA). When the bottom sample reached the end of its range, a second linear actuator (NanoPZ PZA12; not shown in Figure

1a) raised the top substrate out of contact, after which the bottom was returned to its starting position. The top was then placed back on the bottom, and the friction measurement was repeated. This procedure ensured that the sliding always occurred in the same direction and enabled repeated measurements without breaking the seal on the chamber. The output of the force sensor was digitized at a rate of 1 kHz. Friction coefficients were calculated from the ratio of the average shear stress to the normal stress over the last 70% of each sweep. The apparatus was controlled by custom software written in LabView (National Instruments).

The friction apparatus was placed in an environmentally controlled chamber. A thermal plate (Thorlabs MBC12) connected to a recirculating chiller (Thermotek T25SP) provided temperature control. A flow of humidified nitrogen gas provided humidity control. Temperature and humidity were measured with an integrated sensor (Practical Designs THUM). A thermally insulating window enabled visual observation of the experiments.

Figures 1b and 1c show representative data for repeated single-trial friction measurement for homochiral and heterochiral samples of menthol. The normal stress was set to 8.3 kPa (107.5 g over 1.27 cm²). In the experiment of Figure 1b, the homochiral friction of both enantiomers was measured in six repeated sweeps. The difference between the (+)–(+) and the (–)–(–) friction is representative of typical sample-to-sample variation. After six sweeps, the top samples were switched, and the friction was measured for six sweeps of (+)–(–) and (–)–(+) interaction. Mean friction coefficients for the homochiral interaction (averaged over both enantiomers, six sweeps of each) were $\mu_{\text{homo}} = 0.209 \pm 0.011$, and for the heterochiral interactions, $\mu_{\text{het}} = 0.174 \pm 0.007$ (mean \pm sem).

To test whether the lower friction in the heterochiral geometries was an artifact of repeated rubbing of the surfaces, we repeated the experiment with six sweeps of homochiral interaction followed by another six sweeps of homochiral interaction. There was no statistically significant difference between the friction in the first set of six sweeps ($\mu_{\text{homo}}^{(1)} = 0.207 \pm 0.009$) and the second set of six sweeps ($\mu_{\text{homo}}^{(2)} = 0.210 \pm 0.004$) (Figure 1c).

We sought to test whether the lower friction of the heterochiral samples was due to local mixing of the samples to form a racemic compound at the interface. Initially, we sought to form bulk films of the racemate to measure directly racemate–racemate friction. However, these films were too fragile to yield reliable friction measurements.

We next reasoned that in the heterochiral sample the putative interfacial racemic compound would liquefy near $T_r = 33.8$ °C, well below the melting temperature of the bulk pure enantiomers, $T_e = 42.9$ °C. On the other hand, if the two sides of the interface remained enantiomerically pure, then each would melt at T_e . Thus, formation of an interfacial racemic compound was anticipated to manifest as a friction anomaly near T_r .

Figure 1d shows the coefficient of friction for the homochiral and heterochiral interactions as a function of temperature. The heterochiral friction measurement became unreliable at 30 °C due to melting at the interface, and the homochiral friction measurement became unreliable at 35 °C due to melting. The difference in melting temperature implies formation of an interfacial racemic compound during heterochiral friction, though the thickness of this interfacial layer is not known. Remarkably, $\Delta\mu$ was measurably nonzero down to the lowest

temperature measured, 5 °C, well below the melting point of the racemic compound.

If weaker intermolecular forces in the heterochiral case lead to weaker friction, then one might also expect lower viscosity in the racemic melt than in the homochiral melt. We tested for a chirality dependence in the viscosity in the liquid state. Viscosity measurements of (–)-menthol and racemic menthol were conducted using a temperature-controlled rheometer (TA Instruments AR-G2). Shear rate was swept logarithmically from 0.1 to 100 rad/s in 30 steps, at three temperatures: 45, 50, and 55 °C. The average viscosity was recorded for the highest six shear rates, where the viscosity value was independent of shear rate. At 50 and 55 °C, the viscosities of the racemate and the pure compounds were indistinguishable (Figure 1e). At 45 °C, just above the melting temperature of the pure compound, the viscosity of the pure compound was nearly twice that of the racemate.

These results suggest a picture in which differential strength of homochiral vs heterochiral intermolecular forces affects both solid tribology and liquid rheology of the bulk materials. The binary phase diagram of menthol (Figure 2a) shows a lower melting point for the racemate than for the pure enantiomers, consistent with weaker intermolecular forces and lower heterochiral than homochiral friction (Figure 2b).

■ CHIRAL FRICTION OF IBUPROFEN

In ibuprofen, the racemate has a higher melting point than the pure enantiomer, indicating formation of a racemic compound that is more stable than the pure enantiomer (Figure 2c).¹⁷ We thus tested for chirality-dependent friction in ibuprofen. Samples were prepared in the same manner as for menthol. Ibuprofen at room temperature (23 °C) showed higher heterochiral friction ($\mu_{\text{het}} = 0.290 \pm 0.02$) than homochiral friction ($\mu_{\text{homo}} = 0.222 \pm 0.006$) (Figure 2d). These results are consistent with local formation of the racemic compound at the (R)–(S) ibuprofen interface. In contrast to menthol, in ibuprofen the racemate is more strongly bonded than the pure enantiomer.

■ CHIRAL FRICTION OF 1-PHENYL-1-BUTANOL

To determine whether formation of an interfacial racemic compound was necessary for nonzero $\Delta\mu$, we next tested 1-phenyl-1-butanol, which only forms a conglomerate (Figure 2e). The pure enantiomer melts at $T_e = 50$ °C, and the racemic conglomerate melts at $T_r = 16$ °C.¹ We formed thin polycrystalline films of the two enantiomers on aluminum blocks by heating ~30 mg of the powder above T_e and then rapidly quenching the molten film to 4 °C. We tested the friction at 8 °C, well below T_r with a normal stress of 3.5 kPa. Heterochiral friction was ($\mu_{\text{het}} = 0.183 \pm 0.018$), significantly lower than homochiral friction (S on S: $\mu_{\text{homo}} = 0.243 \pm 0.009$; R on R: $\mu_{\text{homo}} = 0.243 \pm 0.014$), implying that chirality-selective friction can occur in the absence of an interfacial racemic compound.

While the molecular origins of chirality-selective friction in this instance are not known, we speculate that the effect may arise from preferential adhesion of crystallites across the homochiral interface relative to the heterochiral interface. Indeed, at the macroscopic level, enantiomer-specific oriented attachment was recently reported for crystals of NaBrO₃, which also does not form a racemic compound.¹⁸

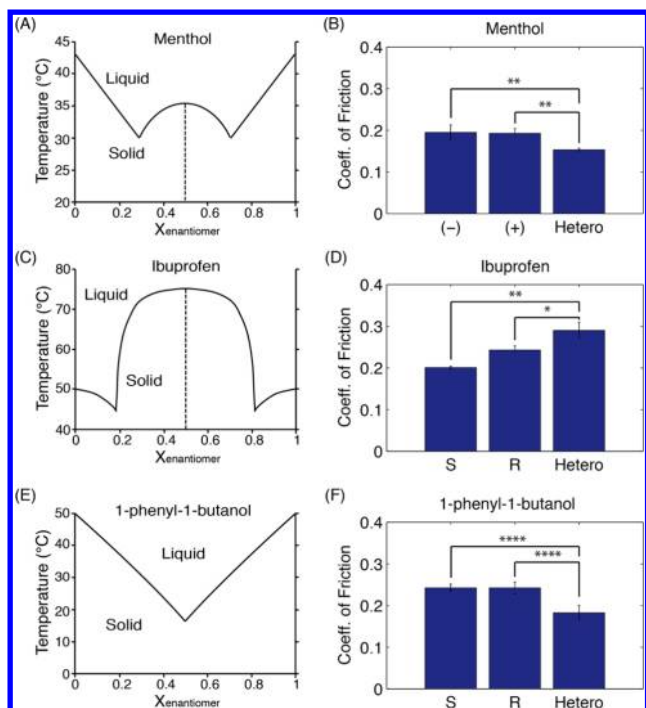


Figure 2. Comparison of chirality-dependent friction in menthol, ibuprofen, and 1-phenyl-1-butanol. In menthol, (A) the racemic compound has a lower melting temperature than the pure enantiomer, and (B) the heterochiral friction is lower than the homochiral friction ($n = 4$ samples, $**p < 0.01$). In ibuprofen, (C) the racemic compound has a higher melting temperature than the pure compound, and (D) the heterochiral friction is higher than the homochiral friction ($n = 3$ samples, $**p < 0.01$). In 1-phenyl-1-butanol, (E) the racemic conglomerate has a lower melting temperature than the pure compound, and (F) the heterochiral friction is lower than the homochiral friction ($n = 6$ sweeps of 1 sample, $****p < 0.0001$) phase diagrams: menthol adapted from ref 16 and ibuprofen adapted from ref 17; 1-phenyl-1-butanol calculated from T_e and T_r data in ref 1 and the Schröder–Van Laar formula. Friction measurements for menthol were performed at 25 °C, 20% relative humidity, for ibuprofen at 30 °C, 20% relative humidity, and for 1-phenyl-1-butanol at 8 °C, 5% relative humidity. Statistical significance was tested using a two-group t -test against the hypothesis that the frictional asymmetry had the opposite sign to the observed value.

DISCUSSION

The correlation between relative friction and relative melting temperature is consistent with prior observations relating relative solubility and relative melting temperature.⁸ In each case the difference between pure compound and racemate is governed by the relative strengths of homochiral and heterochiral intermolecular forces. However, the result with friction is not to be taken for granted: melting and solubility are thermal equilibrium properties relating to bulk material parameters, while friction occurs far from thermal equilibrium and depends on surface properties.

The correlation between intermolecular forces and friction is not a universal phenomenon. In diamond, for instance, the bonds within a crystal are extremely strong, yet the coefficient of sliding friction is low (ranging from 0.03 to 0.5 depending on surface roughness).¹⁹ In diamond, the nature of the forces in the crystal (covalent sigma bonds) is different from the noncovalent forces responsible for friction. In the molecular solids studied here, in contrast, the same noncovalent forces

hold the solid together and mediate friction between adjacent solids.

Only a few macroscopic mechanical manifestations of molecular-scale chirality have been reported. Howard and co-workers proposed and demonstrated that chiral crystals suspended in a rotational flow drift perpendicular to the flow in a chirality-dependent direction.²⁰ Baranova and Zel'dovich proposed a molecular version of the same effect: that a chiral molecule in solution subject to a rotating force field would drift along the axis of rotation.²¹ This “propeller effect” has not been observed at the molecular scale and was only recently reported for micron-scale colloidal particles.²² Because of the r^{-3} dependence of thermal tumbling rate on particle radius, it has not been possible to impose deterministic rotation rates that compete with rotational diffusion for small particles. De Gennes predicted that a macroscopic chiral crystal sliding on an achiral surface (solid or liquid) would undergo a displacement perpendicular to the direction of force and of a sign depending on the chirality of the crystal.²³ This transverse chiral friction is typically small and depends on the macroscopic chiral arrangement of the crystal faces. In irregular or polycrystalline samples, transverse chiral friction is predicted to vanish.

Ever since Pasteur’s pioneering resolution of sodium ammonium tartrate by manual selection of homochiral crystals,²⁴ there has been a need for better ways to separate chiral substances. While practical applications of chirality-selective friction are not immediate, one could imagine applying this phenomenon as a simple means to achieve some degree of separation of a mixed population of enantiomerically pure crystals. For instance, one could flow chiral crystals across a slanted surface composed of a chiral material. Opposite enantiomers should slide at different speeds. Our data indicate that this procedure is conceptually feasible for species that either form a racemic compound or a conglomerate.

Of all the forces that could contribute to friction, only short-range intermolecular forces are sensitive to chirality. The observation of chirality-dependent changes in friction of up to 30% indicates that short-range interactions across the sliding interface are a major contributor to friction in molecular solids.

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Notes

The authors declare no competing financial interest.

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