

remarkable polymorphism, borophene features extraordinary mechanical and electronic properties, including topologically non-trivial electron bands, and (in certain heterostructures) might even host high-temperature superconductivity⁹.

As borophene has been picking up the pace, the graphene research appeared to be slowing down. But then, in 2017, it was re-galvanized by the discovery of superconductivity in twisted-double-layer graphene. Theorists conjectured that if two layers of graphene were stacked so that their high-symmetry axes were twisted at a particular ‘magic’ angle, the bilayer would feature a flat electron band and superconductivity. Experiments vindicated this prediction¹⁰. Twisted-double-layer graphene is formed by dropping one graphene layer on top of another, at a controlled angle. If the twist angle is 1.9°, twisted-double-layer graphene becomes superconducting below about 1 K (ref. ¹⁰). This quickly became a topic of intense research, spread to twisted double layers of other van der Waals materials, and was dubbed ‘twistronics’.

However, until now, borophene had not caught the fire of this second graphene revolution. Borophene has been synthesized at relatively high temperatures, and the growth found to be largely self-limiting to a single atomic layer. As mechanical exfoliation of borophene is not feasible, stacking has remained out of reach so far. While one would expect that a thicker layer may be grown at a lower substrate temperature, it was not clear a priori whether this would result in a double-layer

(DL) borophene or in boron icosahedra such as formed in bulk samples. Liu and colleagues have now settled this question by showing that DL borophene is stable theoretically and demonstrating its formation experimentally (Fig. 1a)⁸.

By combining scanning tunnelling microscopy (STM) and atomic force microscopy (AFM) with ab initio simulations, Liu and co-workers have elucidated the crystal structure of DL borophene, which has two α -phase layers covalently bonded together (Fig. 1b). Field-emission resonance spectroscopy reveals high local work function, suggesting charge transfer from the substrate to the first and the second layer. As in all similar studies of borophene and other ‘X-enes’, the inferred atomic structure should be taken with a grain of salt. While there is good agreement between the simulated and measured STM images, and the proposed structural model is plausible, the structure might not be unique.


This brings us to speculations about the future. Further detailed characterization, by STM, atomic-resolution AFM, low-energy electron diffraction, transmission electron microscopy and angle-resolved photoemission spectroscopy (hopefully revealing Dirac cones), would be useful to provide more information on the DL borophene structure. The DL borophene in Lui and colleagues’ study was grown on Ag(111), leaving open the exploration of other substrates such as aluminium, gold, copper, iridium and so on^{4–7}, which may enable the formation of different crystal structures as well as larger flakes of DL borophene, facilitating further fundamental

and practical studies. Another apparent idea is to try adsorbing and/or intercalating dopants into the DL borophene. A more exigent task is to master borophene lift-off, ideally under vacuum or in an inert-gas atmosphere (as borophene oxidizes in air). That would open the path to manufacturing twisted-double-layer borophene and — given the remarkable polymorphism of borophene and the richness of ensuant band structures — probably trigger another avalanche of studies. But, ultimately, the longevity of borophene — one monolayer, DL, twisted double layer and so on — will depend on whether it finds applications, electronic or otherwise, in the real world. \square

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References

1. Novoselov, K. S. et al. *Science* **306**, 666–669 (2004).
2. Liu, X. & Hersam, M. C. *Nat. Rev. Mater.* **4**, 669–684 (2019).
3. Mannix, A. J. et al. *Science* **350**, 1513–1516 (2015).
4. Li, W. et al. *Sci. Bull.* **63**, 282–286 (2018).
5. Wu, R. et al. *Nat. Nanotechnol.* **14**, 44–49 (2019).
6. Kiraly, B. et al. *ACS Nano* **13**, 3816–3822 (2019).
7. Vinogradov, N. A., Lyalin, A., Taketsugu, T., Vinogradov, A. S. & Preobrajenski, A. *ACS Nano* **13**, 14511–14518 (2019).
8. Liu, X. et al. *Nat. Mater.* <https://doi.org/10.1038/s41563-021-01084-2> (2021).
9. Bekaert, J., Petrov, M., Aperis, A., Oppeneer, P. M. & Milošević, M. V. *Phys. Rev. Lett.* **123**, 077001 (2019).
10. Cao, Y. et al. *Nature* **556**, 43–50 (2018).

Competing interests

The author declares no competing interests.



SUPERLUBRICITY

Sliding on the edge

Heterogeneous microscale contacts between molybdenum disulfide and graphene or hexagonal boron nitride layers demonstrate ultralow friction independent of their relative orientation with residual drag that originates from edge effects.

Oded Hod and Michael Urbakh

Fricition is a major cause of energy loss and wear in numerous mechanical devices operating at various length scales¹. Standard liquid lubricants are widely used to reduce friction in many macroscopic machines including engines,

ball bearings and hinges. Nevertheless, many realistic operational scenarios do not allow for the efficient introduction of such lubricants into the frictional interface. For example, high-pressure and high-temperature conditions may squeeze

out or evaporate the liquid leaving behind a bare high-friction interface. Similarly, vacuum and low-temperature conditions, such as those encountered in outer space, may result in escape or freezing of the lubricant. Notably, the demand

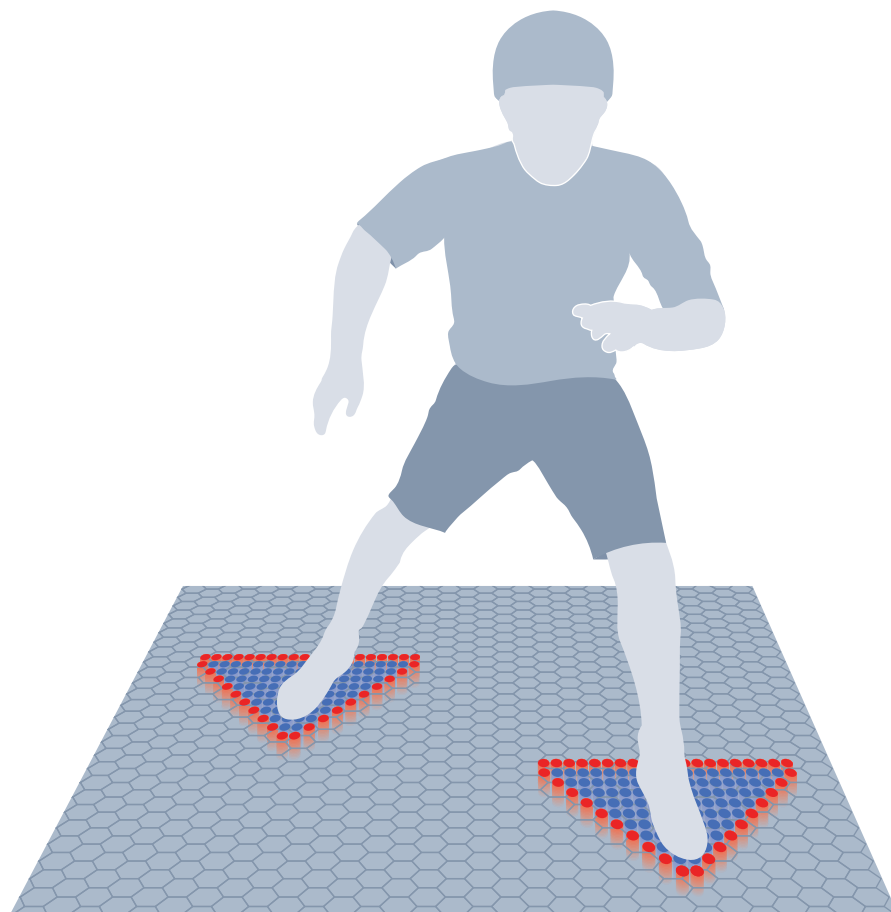


Fig. 1 | Artistic view of increased edge energy dissipation at the heterogeneous superlubric contact of layered materials. The large-lattice-mismatch interface occurring between microscale molybdenum disulfide sliders and a graphitic surface exhibits ultra-low friction characteristics, where the residual friction originates from edge pinning effects.

for alternative lubrication approaches becomes unavoidable when considering device miniaturization, as scaling down traditional lubrication approaches to micro- and nanoscale interfacial confinements is extremely challenging.

During the past two decades, great advances in the basic understanding of the physical processes underlying friction and wear at the atomic and molecular levels led to the discovery of an alternative solid lubrication scheme, termed structural superlubricity^{2,3}. This state of nearly zero friction was demonstrated at nano- and microscale layered material interfaces allowing for durable wearless operation^{4–6}. The secret to obtaining such superlubric sliding lies in the anisotropic structure of chemically inert layered material interfaces that consist of rigid atomic-thick flat layers interacting via weak long-range attractive forces. When the lattices of the contacting layers are stacked in an incommensurate configuration, like two rotated egg-box

foams, efficient cancellation of the lateral surface forces acting between the layers results in a considerable reduction of friction. Such conditions are naturally achieved in heterogeneous layered material junctions, where the inherent mismatch in lattice periodicity of the interfacing layers prevents their lock-in at a high-friction state⁷. This has been demonstrated in recent years for several heterogeneous layered material interface configurations ranging from the nanoscale up to the microscale under ambient conditions and in the presence of contaminants. Importantly, lateral force cancellation, which is a necessary condition for achieving superlubricity, is jeopardized by the existence of surface defects, steps and edges. It is therefore crucial to understand their frictional contribution and to find ways to control and reduce their undesirable effects.

Now, writing in *Nature Materials*, Mengzhou Liao and colleagues have measured ultra-low friction coefficients



for large-lattice-mismatch contacts of graphene or hexagonal boron nitride with molybdenum disulfide — a representative of the transition metal dichalcogenides layered materials family⁸. Unlike previous studies with small-lattice-mismatch contacts, in the present work the friction force is found to be independent of the relative orientation between the atomic lattices of the contacting surfaces. Notably, the authors have devised a clever way of deciphering the separate contributions of edge, surface and step friction. Based on an elegant experimental scaling analysis they found that the main contribution to friction in large-lattice-mismatch microscale interfaces originates from edge pinning effects (Fig. 1). Using detailed molecular dynamics simulations, it was found that edge sulfur atoms demonstrate larger spatial fluctuations compared with their surface atom counterparts, making it more likely for them to be trapped in the local energy minima of the substrate's surface potential. High-resolution transmission electron microscopy measurements, revealing pronounced edge lattice distortions, further support this picture. In the presence of surface steps, the frictional interface tends to lock, leading to a dramatic increase of the friction. Surprisingly, in small-lattice-mismatch interfaces, such as that of graphene and hexagonal boron nitride, friction is found to be dominated by the surface shear forces, rather than edge pinning. This raises fundamental questions regarding the strikingly different frictional mechanisms underlying the superlubric behaviour of small- and large-lattice-mismatched heterogeneous layered interfaces.

The scientific exploration of structural superlubricity constitutes a vibrant field of research with a rapidly developing diverse community of physicists, chemists, materials scientists and engineers. Studying superlubricity may, therefore, lead to unexpected scientific breakthroughs beyond the field of tribology (the science of friction, wear and lubrication), such as microelectronics and energy harvesting^{9,10}, with far-reaching consequences and potential applications, leading to an ever-growing interest in this field from industry. The results presented by Liao and colleagues pave the way for a thorough investigation of structural superlubricity in large-lattice-mismatched layered material interfaces to address many open questions that are of fundamental and practical importance. These include the effects of high sliding velocities, long runs, high external loads, extreme temperatures and the presence of contaminants, among others.

In terms of the computational description some challenges still need to be met, such as the consideration of dedicated force fields (more suitable for describing the anisotropic nature of interlayer interactions in layered material interfaces), the extension of the simulations to surface areas and sliding velocities that better match the experimental conditions, and the inclusion of reactive interlayer potentials that allow for simulating wear effects.

The study by Liao and colleagues is an example of a fruitful collaboration spanning various fields of research, where important advances in the field grow from a synergic interplay between experiment,

computation and theory. We anticipate that this will ignite future collaborative efforts that will further advance the field towards its ultimate goal of achieving robust macroscale superlubricity that may have substantial impact on our world. □

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References

1. Holmberg, K., Andersson, P. & Erdemir, A. *Tribol. Int.* **47**, 221–234 (2012).
2. Shinjo, K. & Hirano, M. *Surf. Sci.* **283**, 473–478 (1993).
3. Hod, O., Meyer, E., Zheng, Q. & Urbakh, M. *Nature* **563**, 485–492 (2018).
4. Dienwiebel, M. et al. *Phys. Rev. Lett.* **92**, 126101 (2004).
5. Liu, Z. et al. *Phys. Rev. Lett.* **108**, 205503 (2012).
6. Koren, E., Lörtscher, E., Rawlings, C., Knoll, A. W. & Duerig, U. *Science* **348**, 679–683 (2015).
7. Song, Y. et al. *Nat. Mater.* **17**, 894–899 (2018).
8. Liao, M. et al. *Nat. Mater.* <https://doi.org/10.1038/s41563-021-01058-4> (2021).
9. Vizner Stern, M. et al. *Science* **372**, 1462–1466 (2021).
10. Huang, X. et al. *Nat. Commun.* **12**, 2268 (2021).

Competing interests

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