On the edge of friction

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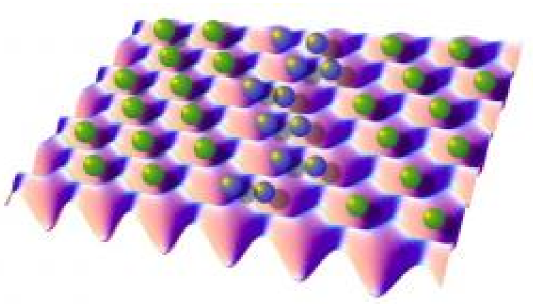

Friction by region: When two microscopic surfaces with the same structure slide over one another, not all particles move at the same time. In fact, the particles in some areas slide (blue spheres), thus distorting their configuration. The other particles (green) stay where they are in the hollows of the surface. Credit: Thomas Bohlein/Ingrid Schofron

(PhysOrg.com) -- The problem exists on both a large and a small scale, and it even bothered the ancient Egyptians. However, although physicists have long had a good understanding of friction in things like stone blocks being pulled by workers into the shape of a pyramid, they have only now been able to explain friction in microscopic dimensions in any degree of detail. Researchers from the University of Stuttgart and the Stuttgart-based Max Planck Institute for Intelligent Systems arranged an elaborate experiment in which they pulled a layer of regularly ordered plastic spheres over an artificial crystal made of light. This enabled them to observe in detail how the layer of spheres slid over the light crystal. Contrary to what one might imagine, the spheres do not all move in unison. In fact, it's only ever some of them that move, while the others stay where they are. This observation confirms theoretical predictions and also explains why friction between microscopic surfaces depends on their atomic structure.

Friction causes the economy enormous losses - but without friction, absolutely nothing would work: the cost of machine parts rubbing against each other as a result of wear, for instance, is estimated to amount to around eight per cent of the German GDP - some 200 billion euros. And that does not even take into account the fact that tectonic plates rubbing together is what causes earthquakes. If a car's tyres or the soles of your shoes did not grip the ground, neither wheels nor feet would be able to move forward. The dominant factors in these examples of friction between large objects have been well understood by physicists for some time now; the countless small irregularities that all surfaces exhibit are instrumental here. They are what lie behind the fact that two large surfaces only touch each other at certain points.

The situation is quite different when two microscopically small surfaces rub against each other. Providing they have been accurately produced, they touch each other with all the atoms of their surface. The researchers from Stuttgart have now observed for the first time how friction takes place on this atomic level. Their experiment also enables them to understand why surfaces with the same structure create more friction when they rub against each other than those with differing structures. "In this way, we are creating the basis for the construction of micro- and nano-machines that are as low in friction as possible," says Clemens Bechinger, Professor at the University of Stuttgart and Fellow at the Max Planck Institute for Intelligent Systems.

Distortions of the surface create movements

Using laser light and electrically charged plastic spheres in a water bath, his team created a two-dimensional model of two surfaces rubbing against each other. As the spheres suspended in the water repel each other electrically, they arrange themselves in a periodically ordered layer. They form a surface. The scientists create the other surface below the layer of spheres using intensive laser beams. They overlap the electromagnetic waves from the beams one above the other so that a light crystal, a type of optical egg carton, is formed. "Using a surface created by light has enabled us to observe the processes that take place on rubbing surfaces directly with a camera - for the very first time," says Thomas Bohlein, who conducted the experiment as part of his doctoral studies. "That's not possible in experiments with three-dimensional objects, because the boundary layer is not visible."

Thomas Bohlein started by precisely calibrating the distance between the hollows in the optical egg carton against the distance between the plastic spheres. One might think that the surfaces would jerkily separate and then snap back into place, one on top of the other, just like two egg cartons would do if you tried to pull one over the other.

But what the experiment showed was a totally different mechanism. When the team drew the plastic spheres across the optical surface, not all of the spheres began to slide simultaneously. In fact, some of the particles moved only within certain areas. In these areas, the spheres left their comfortable hollows and also moved slightly closer together. This phenomenon is possible because the spheres, and also the atoms in a surface, do not sit next to each other immovably - they always have a little room to manoeuvre. And the distortions in the layer of spheres or atoms that occur when they are pulled mean that they do not quite fit back into the surface of the optical crystal. This makes it much easier to pull the particles out of their hollows.

Friction is much reduced in surfaces with different structures

As the researchers pull the particle layer, the compressed zones move through the layer of spheres, with only the particles in these zones able to get out of their hollows. "For the overall layer, it is more efficient to let a distortion zone move through the layer successively rather than to move all of the spheres from one hollow to the next simultaneously," says Clemens Bechinger. The compressed areas that migrated towards the pulling force over the optical surface became ever larger as the team pulled the layer of plastic spheres more strongly.

In the next experiment, the Stuttgart-based physicists pushed the hollows in the optical egg carton slightly closer together so that they did not correspond well with the alignment of the plastic spheres from the start. "As a result, fewer particles find a space in a hollow, and the distortion zones move over the surface much more easily," says Thomas Bohlein.

Physicists had already suspected that local distortions - which they call kinks and antikinks - played the crucial role in the friction between microscopic surfaces. "We have observed these changes in the surface experimentally for the first time," says Clemens Bechinger. "As such, we have confirmed the theoretical predictions about the way friction works in atomic dimensions."

Surfaces without friction will be thinkable

However, the scientists in Stuttgart went one step further. Physicists had hardly any idea what happened in terms of friction between a crystalline surface and a quasi-crystalline surface. Quasicrystals, for whose discovery Shechtman received the Nobel Prize in Chemistry this year, exhibit small areas with a strict order. But this is not repeated regularly in larger dimensions, like in a real crystal.

Thomas Bohlein formed a quasicrystal beneath the crystalline layer of plastic spheres by again skilfully superimposing the laser beams. The plastic spheres came to rest in the hollows of the quasicrystalline surface only at rare intervals, and the friction was drastically reduced compared with that of two crystalline surfaces. "Our experiment provides the proof that one of the reasons why friction on quasicrystalline surfaces is so low is because the structures are incommensurate," says Thomas Bohlein.

The discovery of how friction works on a micro-scale could also have practical consequences. "Above all, the combination of a crystalline and a quasicrystalline surface offers the possibility to reduce the friction in micro- and nano-systems," says Clemens Bechinger. "But it is also conceivable to design surfaces that slide over one another with virtually no friction."

More information: Thomas Bohlein, et al. Observation of kinks and antikinks in colloidal monolayers driven across ordered surfaces, *Nature Materials*, published online: 18. Dezember 2011; DOI: 10.1038/NMAT3204

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