Figure 1 Crystal structure of hexagonal tungsten disulphide, 2H-WS₂.

source of dangling bonds is an edge plane. Furthermore, the propagation of a pre-existing crack in a WS₂ film will break a few covalent bonds and create more unsaturated bonds. If sliding takes place in humid air, such activated surfaces can instantly react with moisture and oxygen in the surrounding environment, forming WO₃. Thus, the tribological (friction and wear) behaviour of metal dichalcogenides is strongly dependent on their environment. For instance, when the test environment is switched from dry nitrogen to humid air², the friction coefficient of a typical WS₂ film can rise from 0.03–0.04 to 0.15–0.20, decreasing its wear life by several orders of magnitude. In contrast, graphite loses its lubricating property in a vacuum, as the complete absence of adsorbed vapours makes it difficult to shear the layers. According to our current understanding, no material can act as a solid lubricant in all these environments. Has such a material now been discovered?

Tenne and co-workers³ first observed closed structures of WS₂, ranging in size from 10 to 100 nm, when they annealed tungsten films at 1,000 °C in a reducing H₂S atmosphere (see Fig. 2). The distance between two fringes in their lattice images is 0.615 nm, the same as the distance between two neighbouring sandwiches in an open 2H-WS₂ structure. Tenne and co-workers³

Figure 2 High-resolution electron micrograph of a WS₂ nanoparticle.

argue that the curling and closure of WS₂ networks was probably induced by thermal stresses (1,000 °C is a fairly high temperature) and facilitated by structural defects such as edge dislocations, or by contaminant atoms, such as oxygen, that came from the quartz substrate. The authors have also made nanoparticles of WS₂ (HN-WS₂) in gram quantities by a sol–gel reaction¹.

The dangling bonds that are responsible for causing oxidation in layered 2H-WS₂ structures are no longer present in HN-WS₂ particles. Does this mean that we now have a super solid that can effectively lubricate in all environments? The intracrystalline slip that is responsible for creating smooth transfer films is no longer present in this powder, as appreciable shear between inner and outer closed layers is almost impossible. By the same token, HN-WS₂ powder cannot be burnished like the traditional layered structures. Indeed, Tenne and colleagues¹ had to roughen the substrate and use a drop of mineral oil to avoid runaway of the nanopowder during friction measurements. Yet the friction coefficient and wear rate for nano WS₂ powder measured in oil were superior to those of traditional WS₂ and MoS₂ powders¹. This suggests that a different mechanism is controlling the tribological behaviour of nanoparticles.

The mechanism of lubrication in the case of hollow nanopowder appears to be one of rolling and not sliding. By virtue of their extremely small size, the HN particles can fill the submicrometre-sized valleys between asperities and prevent asperity contact between mating surfaces. This, coupled with their rounded shape, opens the possibility that they undergo rolling friction at the nanometre level. Furthermore, elimination of dangling bonds makes the HN particles chemically inert, so the particles are less likely to stick to the substrate, or to one another. Their hollow-cage structure imparts high elasticity, and elastic deformations (as opposed to inelastic deformations) diminish the energy dissipation associated with friction. These are some of the characteristics that make the hollow nanoparticles of metal dichalcogenides potential candidates for miniature rolling-element bearings.

Perhaps, in the coming decades, we might see a micrometre-sized rolling-element bearing using hollow nanotubes of metal dichalcogenide. But even in the near future, these small, round, inert nanoparticles should find some applications in powder lubrication, and as additives in lubricating oils. □

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Daedalus

A science futures market

When a manager starts to depend on performance indicators, he is losing his grip. He should know what his concern is up to, without juggling arcane ratios. And once performance indicators are taken seriously, doom is certain. The organization switches its goals from whatever it should be doing, to maximizing the indicators.

On this criterion, scientific research is in a bad way. Performance indicators abound — impact factors, citation counts, publications per head or per grant dollar, and so on. Mutual backscratching cliques cite each other furiously in all their papers; journals parasitized by such publications proudly proclaim their impact factors; grant money flows to individuals and organizations who can show the best performance indicators. Hence the delight and outrage over the recent research-assessment ranking of UK universities.

Daedalus now has a better way. Science is no longer a collective endeavour to understand the physical world; it is a competitive struggle to acquire grant money. The time has come to put it on a sound capitalistic basis. So Daedalus proposes a scientific stock exchange. University departments, and even individual scientists, could issue shares in their research programmes, and shareholders would receive a proportion of each grant subsequently won by the issuer.

At once the 'invisible hand' of the market would work its benevolent magic. Researchers would issue prospectuses arguing the strength of their teams, the brilliance of their hypotheses and the convincing nature of their pilot experiments. The grant-worthiness of such claims would be judged by shrewd and critical scientific investors. The intellectual debate would be sharpened by the attempts of competing shareholders to talk up the projects they had backed, or to criticize ones in which they had taken a 'stag' position. In the same way, the scientific grapevine would instantly evaluate alleged breakthroughs or setbacks, and signal its opinion through the relevant share prices.

Research would be transformed. Any scientist could obtain prompt 'seed-corn money' for his ideas by issuing shares. Progress on all research fronts could be assessed daily in the financial papers. And a whole new scientific career would open up. Elderly researchers would no longer see administration yawning inescapably in front of them. Their experience and insight would gain them steady money punting on the scientific market.

David Jones