

Figure 2 | A wide range of toughening mechanisms can be observed and quantified by X-ray computed tomography, many of which are critical to the toughening of high-temperature ceramics. Image reproduced with permission from ref. 9, © 2012 AR.

also be used to evaluate the pull-out of SiC fibres from single SiC–SiC composite tows at 1,750 °C (Fig. 1c), thereby establishing

the interfacial frictional sliding stress for pull-out (0.4 MPa versus 2 MPa at room temperature) and hence the capacity for

energy absorption¹. Indeed, the authors' X-ray microtomography approach and the wealth of information it can generate should speed up the optimization of the interfacial properties of materials under static and fatigue loads to further tailor their high-temperature toughness. □

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NANOSCALE HEAT TRANSFER

Single hot contacts

Measurements of heat transport across polished nanoscale contacts formed between the tip of a scanning thermal microscope and a surface support the notion that their true contact area consists of discrete atomic contact points.

Yifei Mo and Izabela Szlufarska

What does the interface between two solid objects in close contact look like on a molecular scale? What physical and chemical processes take place at such an interface? And how are forces, heat or electric currents transferred across it? The fact that these questions remain for the most part unanswered underlines the fundamental difficulties in understanding nanoscale friction, which in great part arise from the lack of well-developed experimental techniques that would allow imaging of individual atoms and molecules when they are buried in between two surfaces in close contact. Writing in *Nature Materials*, Bernd Gotsmann and Mark Lantz show that measurements of the pressure dependence of heat transfer across polished nanoscale contacts agree with a model that assumes quantum thermal transport across individual atomic contact points¹. Their findings provide indirect evidence on the nature of nanoscale roughness.

At the macro- and microscales, the true or real contact area between two solid bodies — which governs most physical behaviour at the interface, including friction and heat transfer^{2,3} — consists of a large number of discrete contact points (Fig. 1a,b). At the nanoscale, however, the nature of the true contact area, or even whether the contact area can be well defined, are still a matter of debate^{4–6}. On the basis of molecular simulation results, it has been proposed that in many situations nanoscale contacts cannot be treated as smooth (Fig. 1c), but instead they can be viewed as consisting of discrete atomic contact points that behave analogously to real contacts at larger length scales⁴ (Fig. 1d). Still, limitations in experimental characterization techniques have precluded experimental verification.

The work of Gotsmann and Lantz is a strong voice in this debate. Using a scanning thermal microscope (Fig. 2a),

the researchers found that the thermal conductance across single-asperity contacts that are tens of nanometres in size increases linearly with the applied normal pressure (Fig. 2b). Strikingly, this dependence is inconsistent with the common assumption that a nanometre-sized contact is atomically smooth and continuous. A straightforward explanation is that the contact is rough, and hence that only a small fraction of the interfacial area contributes to the heat transfer. Furthermore, the researchers discovered that existing theories of thermal transport, which assume that thermal conductance is not quantized, predict a much weaker dependence of heat conductance on pressure than the dependence measured experimentally. By comparing their experimental results to different contact models, Gotsmann and Lantz concluded that the true contact area of a nanoscale contact comprises individual discrete atomic contact points

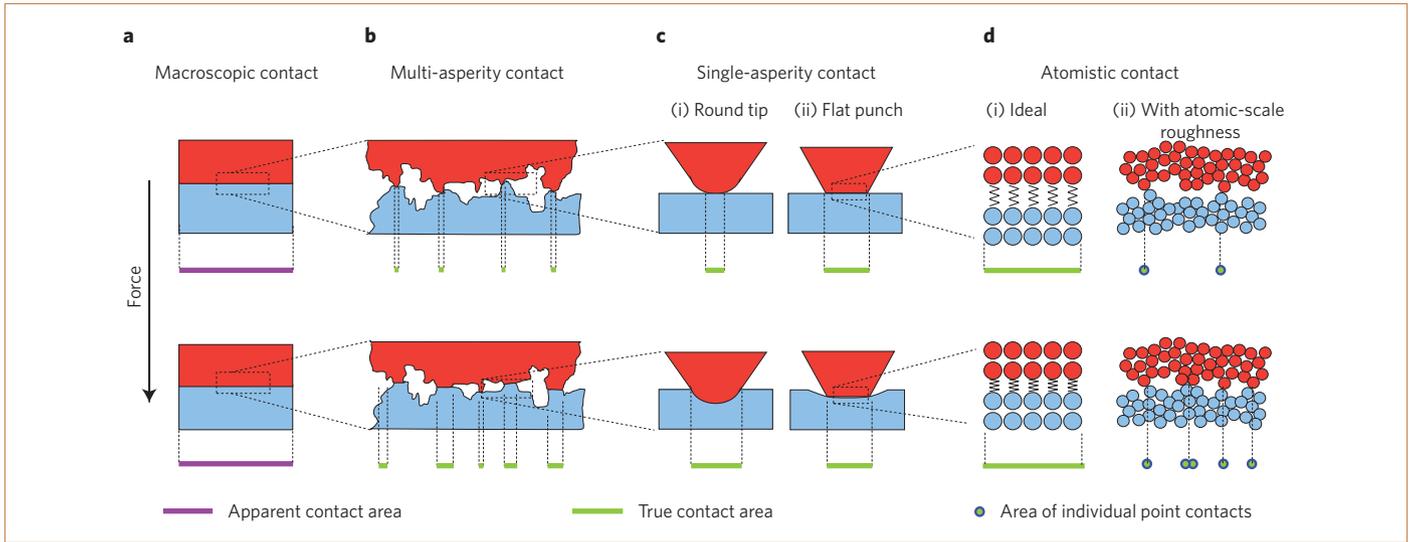


Figure 1 | Contact models for macro- and nanoscale objects¹. **a,b**, Macroscopic contacts appear smooth (**a**), but they consist of a large number of contact points (**b**). **c,d**, Nanoscale single-asperity contacts appear to be smooth (**c**), but depending on the applied force and details of the surface they can be treated as atomically smooth (**d**, i) or atomically rough (**d**, ii).

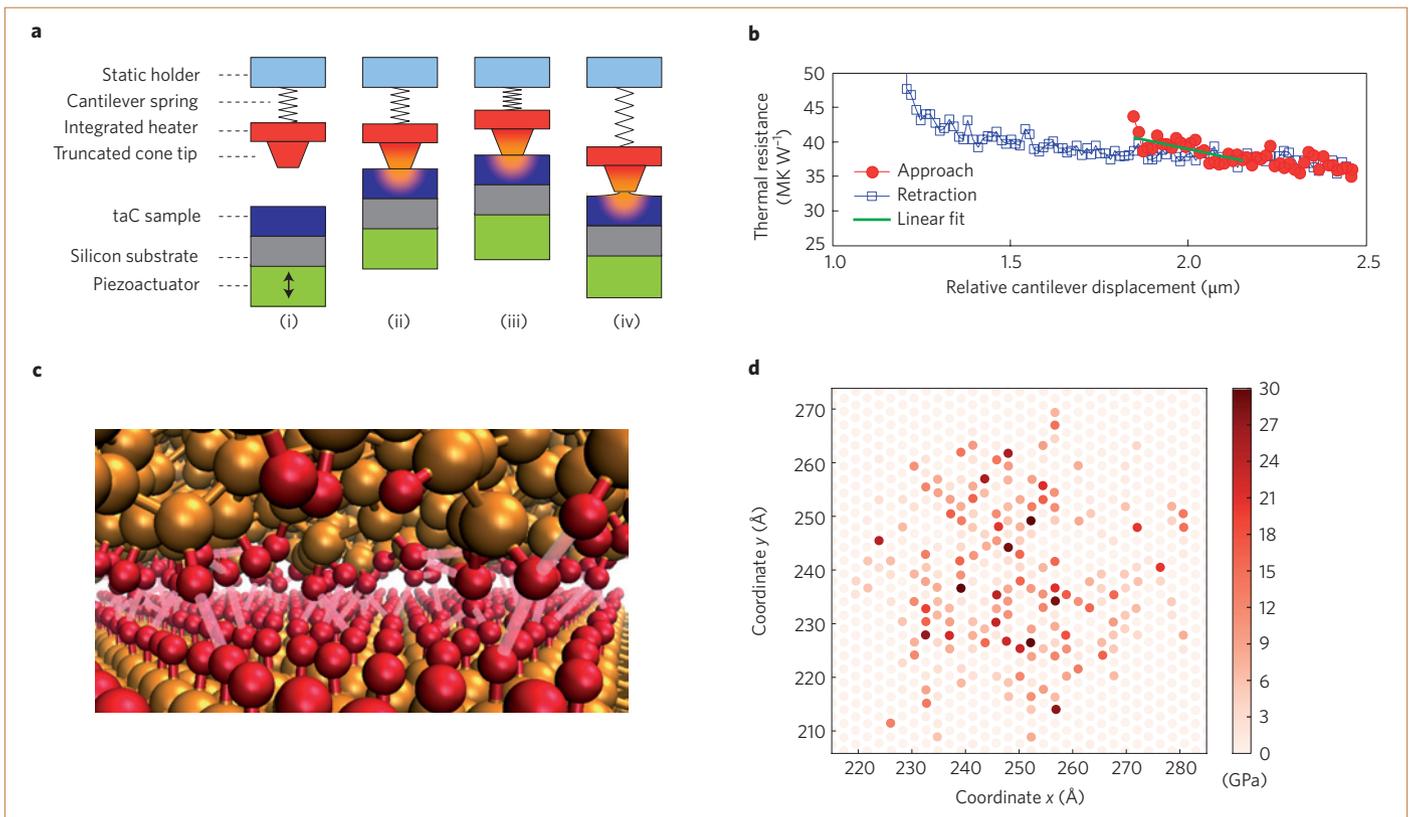


Figure 2 | Thermal resistance and structure of a nanoscale contact. **a**, Schematic of the experiments performed by Gotsmann and Lantz, in which a sample of tetrahedral amorphous carbon (taC) is pushed against a polished nanoscale probe tip by a piezoactuator and then retracted¹. **b**, Thermal resistance across the contact during approach and retraction of the sample¹ (the green line is a fit for the relative cantilever displacements corresponding to the load forces used during tip polishing). **c**, Molecular dynamics simulations of nanoscale contacts showed that only a small fraction of atoms at the interface are chemically interacting⁴ (indicated by the semitransparent pink cylinders). **d**, A rough contact is characterized by a distribution of the normal pressure that is highly concentrated on a small number of atoms.

(Fig. 2c) — in agreement with previous computer simulations⁴ (Fig. 2d) — and that the thermal conductance is quantized⁷.

In fact, the observed dependence of heat conductance (and therefore also true contact area) on pressure is consistent

with the idea that discrete contacts at the nanoscale behave similarly to rough contacts at larger length scales.

In classical thermal-transport theories interface roughness is usually viewed as a source of scattering⁷, whereas quantized thermal transport has only been observed for one-dimensional nanowires⁸. The work by Gotsmann and Lantz demonstrates that in rough mechanical contacts the total heat transferred across an interface is the sum of heat transferred through a collection of one-dimensional channels, that is, atomic-level contact points. Thus, the work challenges existing theories of heat transfer across interfaces when applied to small contacts such as those present in microelectromechanical systems, and it provides a fresh framework for thinking

about heat transfer across nanocontacts. Finally, the researchers' experimental technique for contact characterization opens up opportunities for simultaneous measurements; for example, it may be possible to assess contact-area evolution during friction experiments instead of relying on *ex situ* surface-characterization approaches. Indeed, obtaining dynamic properties of the interface in a sliding contact, which is at present an outstanding challenge in the field of friction, may soon become possible. □

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MAGNETOCALORIC MATERIALS

Strained relations

The magnetocaloric effect could form the basis for efficient refrigeration technologies. The finding that large and reversible magnetocaloric effects can be induced through a strain-mediated feedback mechanism may expand the range of available magnetocaloric materials.

Per Nordblad

An area of modern life in which thermodynamics plays a central role is refrigeration. Its widespread use in household and industrial applications has driven a need for cheap and environmentally friendly processes that might replace the costly approaches based on mechanical work. One promising strategy is to take advantage of the thermodynamic changes associated with the varying magnetization of materials exposed to a magnetic field, a phenomenon known as the magnetocaloric effect. This requires magnetic materials with suitable intrinsic properties that maximize the thermal response associated with the change in magnetization¹. Although magnetic refrigeration has become a standard technique in low-temperature physics, the relatively few materials with large magnetocaloric properties at higher temperatures has restricted its use in commercial applications.

Writing in *Nature Materials*, Xavier Moya and colleagues now describe experiments that potentially overcome this limitation and open the door to a new range of materials with giant magnetocaloric effects². The researchers study epitaxial films of $\text{La}_{0.7}\text{Ca}_{0.3}\text{MnO}_3$ (LCMO) grown on BaTiO_3 (BTO) substrates. Under ordinary conditions, LCMO becomes ferromagnetic below

260 K, but its magnetocaloric properties are modest. However, when placed next to BTO the picture changes: BTO undergoes a structural transition at around 200 K, which in turn strains the LCMO film and induces a change in its lattice parameters. On cooling, this structural change causes a jump in the magnetization of LCMO, which results in a substantial magnetocaloric effect, albeit extrinsic in origin.

The magnetocaloric effect is an adiabatic process that occurs without an exchange of heat with the surrounding environment taking place. Consequently, when an applied magnetic field is cut off,

the entropy associated with the magnetic moments of a material increases and, in turn, its lattice entropy must decrease, resulting in a drop in temperature of the material. This effect is largest close to the transition temperature of ferromagnets, where the magnitude of the magnetization changes most rapidly with temperature. Gadolinium has been widely studied as a magnetocaloric material because it is ferromagnetic at room temperature and has a sizeable magnetic moment. However, as for all materials undergoing continuous (or in the language of thermodynamics, second order) phase transitions, its

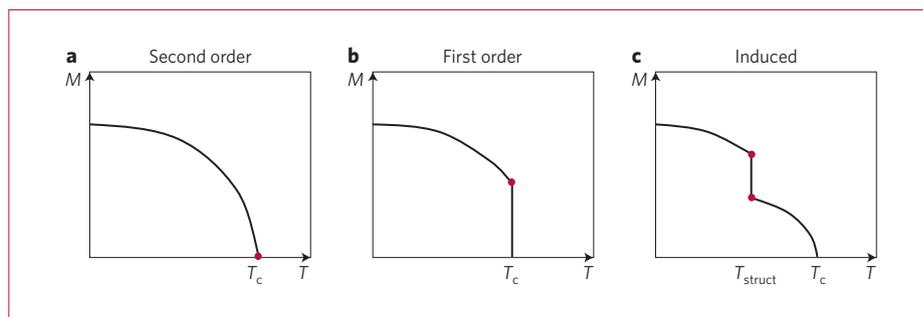


Figure 1 | Phase diagrams describing the change in magnetization (M) as a function of temperature (T). **a**, Second-order phase transition, whereby M changes continuously with T up until the critical point (T_c). **b**, First-order phase transition whereby M changes discontinuously at T_c . **c**, Scenario observed by Moya *et al.* for LCMO on BTO, whereby a discontinuous jump in M of LCMO is induced by a structural transition in the BTO substrate at T_{struct} .