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The Material Is the Machine

Kaushik Bhattacharya and Richard D. James

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corona); the Solar Dynamics Observatory (to study solar activity with full-disc, TRACE-quality images captured every 10 s in a range of wavelengths), and Solar Orbiter (which will match the solar rotation and journey out of Earth's ecliptic plane to view the solar poles). The spatial, temporal, and spectral resolution of the spectrometers and atmospheric imagers used by these missions (up to an order of magnitude higher than those of today's instruments) will be vital for finally solving the puzzle of how the solar corona is heated.

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APPLIED PHYSICS

The Material Is the Machine

Kaushik Bhattacharya and Richard D. James

For more than a century, materials scientists have studied the micrometer-scale needles and platelets that occur in many materials. In martensitic materials—which undergo a reversible, diffusionless solid-to-solid phase transformation in which the underlying crystal lattice spontaneously distorts—the patterns of microstructure resemble a jigsaw puzzle (see the first figure). Recent studies suggest that the characteristic distortions of such martensitic materials can be exploited to create tiny machines.

Imagine that each piece of the puzzle undergoes one of several characteristic distortions. For example, take a crystal with atoms arranged on a cubic lattice and focus on a single cube (a unit cell) with atoms at each corner. In a simple cubic-to-tetragonal transformation, this cube spontaneously elongates along one cube edge. But, by symmetry, it could also elongate along another cube edge. In this case, there are three characteristic distortions and thus three variants of martensite. Martensitic materials have the remarkable property that the puzzle fits together even after undergoing the characteristic distortion, thereby achieving a complex but coordinated motion.

The typical size of the individual domains—the pieces of the jigsaw puzzle—can range from nanometers to millimeters and is determined by a complex interplay between the bulk and interfacial energies (*1–4*). This length scale is of interest to researchers trying to make smaller and smaller devices. These researchers have used microelectromechanical systems technology to create intricate patterns on silicon films and multilayers that reproduce, in scaled-down form, the gears, levers, cantilevers, and electromagnetic motors of everyday machines.

This approach has led to devices that can perform unique tasks. An example is digital light projection (*5*), where hundreds of mirrors on a single chip are moved independently to create images on a television or movie screen. But each mirror is made of multiple moving parts that are fabricated on silicon and driven by electrostatic actuators. The complexity thus increases with decreasing size, and there are inherent limitations on how small these devices can reliably be made. Martensitic materials may overcome this limitation. By depositing thin films of a martensitic material and patterning it appropriately, one can control the characteristic distortions to make the domains perform as the components of the machine.

Another potential advantage of martensitic materials was suggested by Krulevitch *et al.* (*6*). Among a broad array of actuator systems, the martensitic material NiTi exhibits the largest known work output per unit volume of the actuator. This performance results from a unique feature of martensitic materials: The linear transformation that defines the distortion of each domain is exactly the same as that of the atomic unit cell of the lattice. The free energy of a domain equals the free energy of its smallest unit cell times the number of unit cells in that domain. A large fraction of this free energy can be transferred to the environment via interaction with a loading device.

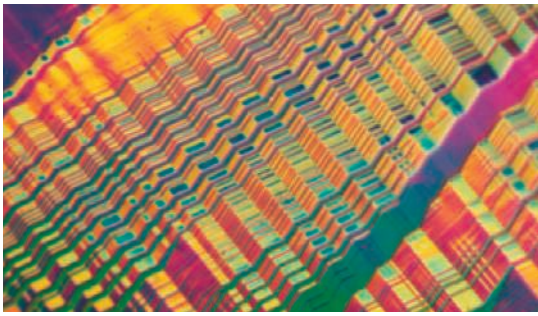
A martensitic material thus provides a direct link between the macroscopic environment and its fundamental unit cell. Devices based on this property, such as micropumps, microvalves, and micropositioners, are now reaching commercialization (*7–9*). They use polycrystalline films on flexible substrates and exploit the properties averaged over the many domains. Their success motivates the more ambitious quest to use the individual domains as machines.

The microstructure of bulk martensitic materials can be predicted from theory, but until recently this was not possible for thin films of these materials. A powerful new mathematical method, called Γ convergence (*10*), can answer precisely such questions. The resulting theory for thin-film martensites (*11*) has led to a surprising prediction: The interfaces between phases (or, more precisely, between the variants of martensite) in a thin film are completely different from those in bulk material and have a much simpler structure.

This prediction paves the way for the design of a machine: One must pattern the film such that it is released along the predicted interfaces (see the second figure, left panel). In effect, one thus defines the jigsaw puzzle by patterning. This patterning must use the compatible interfaces between phases to select a unique puzzle with a useful distortion.

A proof-of-principle of these concepts has been demonstrated in a single-crystal thinned foil of CuAlNi by Cui and James (see the second figure, right panel) (*12*). The orientation of the foil was chosen so that orthogonal interfaces predicted by the thin-film theory would separate the phases. The foil was then confined outside of a square bounded by these interfaces. This arrangement defined a rather simple jigsaw puzzle with four triangular pieces, which stood up like a tent when cooled and collapsed flat upon heating.

In a similar manner, a film released on a strip defined by the predicted interfaces should form a "tunnel." Upon heating, the tunnel would collapse onto the substrate. One can envisage vast networks of such tents and tunnels, with collapsed and un-



Martensite jigsaw puzzle. Bulk CuAlNi contains six different variants of orthorhombic martensite that form a jigsaw puzzle. The horizontal dimension of this image is 1.4 mm.

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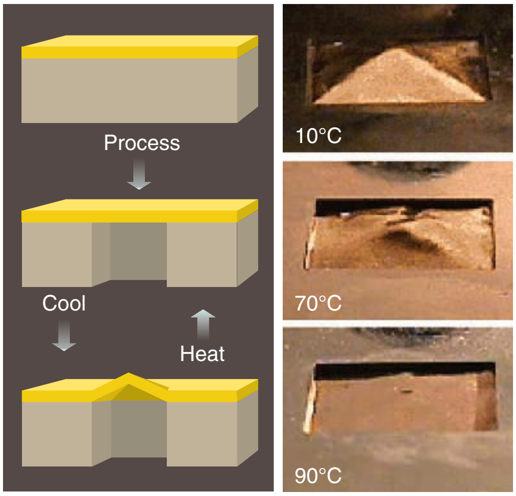
K. Bhattacharya is in the Division of Engineering and Applied Science, California Institute of Technology, Pasadena, CA 91125, USA. E-mail: bhatta@caltech.edu
R. D. James is in the Department of Aerospace Engineering and Mechanics, University of Minnesota, Minneapolis, MN 55455, USA. E-mail: james@umn.edu

collapsed regions driving bits of fluid around. Such networks could be used in microfluidics devices such as labs on chips.

Recent efforts are focusing on enabling this general process on the micrometer and smaller scales. This presents a huge challenge, requiring the synthesis of single-crystal films of martensitic and closely related materials that have complex crystal structures and nonstoichiometric compositions. Recently, researchers armed with a variety of methods have grown such films of perovskite oxides (*13*–*15*) and alloys related to Ni$_2$MnGa (*16*). (The former are ferroelectrics, whereas the latter alloys are both martensitic and ferromagnetic.) These materials have another interesting feature for material-as-machine: In addition to the distortion, the individual domains are also electrically or magnetically polarized. Thus, instead of causing the shape change by heating or cooling, one can do it by applying a magnetic or electric field, opening up a host of possibilities including remote actuation. Early results are encouraging. For example, Nagarajan *et al.* (*17*) have shown that the domains can be altered by patterning the film and that this method can be exploited to build small-scale actuators.



How materials may act as machines. (Left) Schematic cross section of a film, released on a square, showing a tent-like deformation produced by phase transformation. **(Right)** Realization of such a deformation in a CuAlNi foil, released on a 1 cm by 1 cm region, produced by heating and cooling the film.

Given their huge work output per volume and their small scale, materials-as-machine may be best suited for biomedical applications. At these microscopic scales, the forces needed to overcome the enormous constraining effects of both surface tension and viscosity are daunting for microelectromechanical systems. The ideal machine for such applications might in fact be made of proteins.

It turns out that nature already uses such a material-as-machine. Bacteriophage T-4 virus has a tail sheath made of a single-domain protein that undergoes a martensitic transformation (*18*). During invasion of the host, virus-host interactions trigger the transformation in the sheath, driving a hollow protein needle through the cell wall of the bacterium through which its DNA is passed. It would be fascinating to create a human-made analog of the virus's tail sheath. Recent progress in the theory, synthesis, and fabrication of martensitic materials suggests that this idea is ready to explore.

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EVOLUTION

Policing Insect Societies

Francis L. W. Ratnieks and Tom Wenseleers

The London Bobby is a reassuring symbol of civic order (*1*). But this symbol is also a reminder that human societies have conflicts. Insect societies, too, experience internal conflicts (*2*), and research increasingly shows that policing is important to resolve these. Within both human and insect societies, conflicts arise because the interests of individuals differ. In insect societies, conflict revolves around reproduction. Reproducing individuals gain by being more closely related to the young males and queens reared in their colony. By reproducing, society members also exploit the colony and this can be costly. First, uncontrolled reproduction upsets the division of labor between queen and workers and results in a less efficient colony. Second, the offspring reared are often genetically less related and so are less valuable to other society members.

To prevent exploitation, social insects have evolved several methods of policing. The best known is "worker policing," whereby workers kill eggs laid by other workers. This phenomenon was first discovered in the honeybee 15 years ago (*3*). Since then, it has been discovered in more than 15 species of bee, wasp, and ant. This past year alone, five more insect species—two species of British wasp (*4*) and three ant species from Florida (*5*), Brazil (*6*), and Finland (*7*)—have been added to the list.

In addition to reducing reproduction by workers, policing also acts to regulate the development of females into distinct queen and worker castes, and to prevent excess females from developing into queens (*8*). When different species are compared, one important overall conclusion emerges: More effective policing results in fewer individuals acting selfishly. There are other striking parallels to human society: Insect policing relies on both detection and prevention, and individuals sometimes attempt to evade policing (see the figure).

In the life of any female bee, wasp, or ant, there are two points at which she may try to reproduce. The first is when, as a larva, she starts developing into either a queen or a worker. In most species, queens are morphologically specialized for egg laying and are often incapable of working. The second is when, as an adult worker, she decides whether to activate her ovaries to lay eggs. In most species, workers cannot mate yet retain ovaries. Therefore, they can lay unfertilized eggs, which develop into males if reared.

Young female larvae of bees, wasps, and ants are usually totipotent, that is, they have the potential to develop into either a queen or a worker. A larva is often better off developing into a queen, yet policing

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The authors are in the Laboratory of Apiculture & Social Insects, Department of Animal & Plant Sciences, University of Sheffield, Sheffield S10 2TN, UK, and the Institute of Advanced Study, Berlin 14193, Germany.

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