shape-memory alloys, electric-field control of shape memory is unfeasible, and they are restricted to operating at low frequency owing to slow responses to temperature changes (even at the nanoscale). The possibility of using electric fields to actuate ferroelectric nanoscale oxides should then enable easily controllable actuation at higher frequencies in nanoscale shape-memory devices. ❒

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DIRECTED COLLOIDAL ASSEMBLY

Printing with magnets

Planar patterns of colloidal microparticles have been manufactured with high yield over square centimetre areas by using magnetic-field microgradients in a paramagnetic fluid. This approach could evolve into technology capable of printing three-dimensional objects through programmable and reconfigurable 'magnetic pixels'.

Changqian Yu, Jie Zhang and Steve Granick

As the manufacturing needs of modern society evolve, so must do materials research. This is exemplified by printing, an ancient but evergreen idea. Printing technologies have inspired new manufacturing paradigms, from the woodblocks invented almost two millennia ago to its advanced forms that underpin the digital age (such as lithography, chemical stamping and inkjet printing) to the increasingly important three-dimensional (3D) printing — already widely employed for rapid prototyping. In fact, 'ink' has become a metaphor for depositing, with precision and on demand, countless tiny objects such as nanoparticles, viruses or transistors. Even living tissues and organs can be printed.

Because most printing methods work in air, it has been a challenge to 'print' order into microscopic objects that remain suspended in liquids. Perhaps because methods to do so are so poorly developed many scientists have taken the self-assembly route, which is the pre-eminent approach to organize objects experiencing Brownian motion into the 'self-organized' state (that is, the state of lowest thermodynamic free energy). Passive self-assembly has the appeal of working well in fluids, yet typically suffers from low yield and unwanted by-products, and its successes can be difficult to generalize and scale up. Hence, the appreciation for methods that direct colloidal assembly by external control is growing. In this spirit, by building on earlier proof-of-concept work that showed that magnetic fields can place diamagnetic and paramagnetic particles into programmed positions[1], Bartosz Grzybowski and collaborators report in *Nature* how to print a spectrum of colloidal objects — polymeric particles, silica particles, even live bacteria — suspended in a paramagnetic fluid[2]. By using magnetic-field microgradients produced by metal grids embedded in a rubber layer a few hundreds of nanometres thick that is placed on a permanent magnet (Fig. 1a), the authors show that beautiful arrays of complex microstructures can be assembled with high yield over square centimetre areas (Fig. 1b). Grzybowski and co-authors refer to this assembly approach as 'magnetic moulding' because solutions of paramagnetic salts regulate the response of the colloids to the magnetic fields; the solution becomes in fact part of the mould. Interestingly, the controlling magnetic fields extend into the bulk fluid and therefore the method is able to assemble

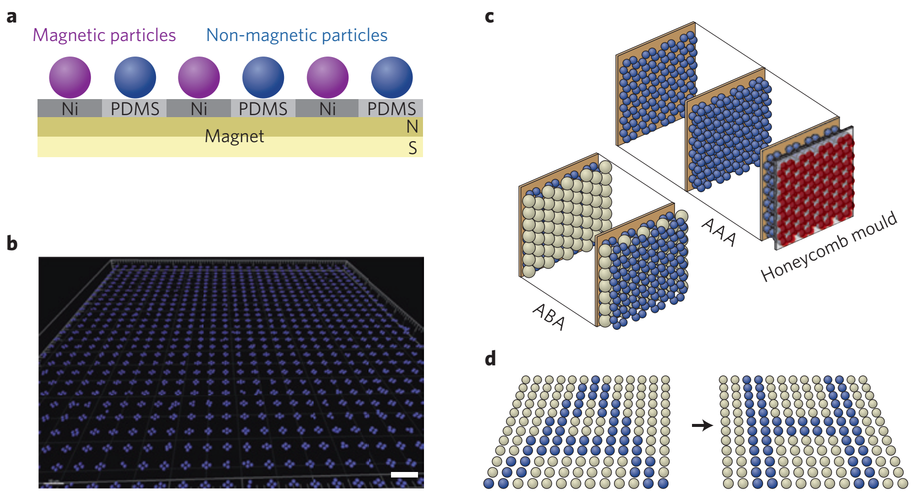

Figure 1 | Magnetic moulding could form the basis of 3D printing technology for colloidal materials. **a**, Magnetic-field microgradients produced by Ni grids embedded in a poly(dimethyl siloxane) (PDMS) layer and placed on top of a permanent magnet can act as magnetic moulds for both magnetic and non-magnetic colloidal particles[2]. **b**, As exemplified by the confocal image of a monolayer of colloidal tetramers, magnetic moulds can be used to assemble colloidal objects over large areas[2]. Scale bar, 10 μm. **c**, Taking inspiration from the rapid reprogrammability of electronic displays, magnetic pixels might be designed for layer-by-layer 3D printing, here exemplified conceptually by the layer-by-layer deposition of colloidal spheres to produce two families of 3D lattices (AAA and ABA packings) whose pore size, pore chemistry and colloidal arrangement are precisely controlled at each deposition step. **d**, The concept of reconfigurable magnetic pixels remains an engineering dream. Panels **a** and **b** reproduced from ref. 2, © 2013 NPG.

few-layer structures that extend beyond the planarity that is typical of conventional printing. If desired, the printed structures can be made permanent with appropriate chemical modifications.

Magnetic-mould techniques could potentially enable 3D printing of colloidal structures. It's easy to imagine changing the position of the magnetic mould at different steps of the printing process. Then, as with conventional additive manufacturing, scaled-up bulk materials could be obtained by means of layer-by-layer deposition while fixing the previous layers permanently (Fig. 1c). Because in magnetic moulding the resolution of the magnetic pixels is defined by the size of the printed objects and the pattern, the approach does not suffer from resolution limitations of existing inkjet 3D printers. Precision devices (such as photonic devices[3]) may benefit from this. What's more, it may be possible to make magnetic moulds with 3D shapes by using stereolithography[4]. In fact, magnetic-mould scaffolds with non-planar shapes, such as hollow tubes, may achieve even higher levels of control of the assembly process.

Moreover, if magnetic moulding and passive self-assembly were to be combined synergistically[5], the magnetic-template principle put to practice by Grzybowski and colleagues could be generalized to provide programmability and reconfigurability on demand. Achieving this should be possible by using reconfigurable magnetic pixels (Fig. 1d), with electromagnets in place of permanent magnets. Today, it is routine to switch pixels on visual displays at video rates; one day, one may achieve similar speed and control magnetically by combining the existing merits of electronic displays with the added advantage of magnetic fields. For example, by incorporating dynamic magnetic control into patterned moulds it may become possible to routinely reconfigure the lattice constant, symmetry of packing and even the specific arrangement of crystal packings of multicomponent colloidal systems by switching their magnetic moulds on the fly.

However, for these dreams to come true much difficult engineering lies ahead. Only in science fiction can the designs of materials be reconfigured as easily as electronic images are switched on a screen today. And as crazy as it may sound, the idea of on-demand reconfiguring of printed objects — analogous to transforming a sword into a ploughshare, for instance — belongs to the visionary's mind. We do not yet know how to program, print and reconfigure 3D materials with the speed and versatility now possible with visual images. While we wait for breakthroughs to arrive, methods such as that of Grzybowski and colleagues give us hints as to how printing technology may develop. ❐

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