associated with cancer. This suggests that a less 'cancer-centric' analysis might reveal other genes that can drive the expansion of clones in normal tissue.

We are only starting to map the extent of genetic alterations in normal tissues. The next challenge will be to fully understand their role in healthy tissues and in disease states. ■

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MATERIALS SCIENCE

# Hardening mechanisms scaled up

**Metals can be strengthened by mechanisms that work on the atomic scale. These same mechanisms used at a much larger scale have been found to also strengthen materials that contain hierarchical, engineered substructures.** SEE ARTICLE P.305

GANG SEOB JUNG & MARKUS J. BUEHLER

Atomic-scale mechanisms that affect the structural properties of materials can also inform the design of new materials needed for engineering, such as high-performance alloys. On page 305, Pham *et al.*[1] report their use of 3D printing to translate some atomic-level hardening mechanisms typically found in crystalline materials to a larger scale. The resulting 'architected' materials contain substructures that are designed to mimic atomic arrangements in crystal lattices. Their work provides a fresh approach for developing designer materials and could facilitate the application of hardening mechanisms to different materials and on different scales.

Engineers have a diverse array of tools at their disposal for designing and constructing new materials. Additive manufacturing[2], also known as 3D printing, is one such tool that could revolutionize the field of materials fabrication, in part because it can produce almost any geometric feature. An idea that has received much attention involves using additive manufacturing to make materials that have complex microstructures[3], which are difficult to construct using conventional methods.

Natural materials such as bone, silk and nacre have exceptional properties that many conventional engineering materials lack. These properties arise from the materials' complex hierarchical structures — the macroscopic materials are built up from repeating patterns of smaller building blocks at several different length scales. Additive manufacturing has been used to reconstruct the hierarchical patterns of building blocks found in natural materials, but instead using conventional materials. The products have mechanical properties — such as high toughness, strong impact resistance and the ability to bear heavy loads — that exceed those of the conventional materials[4], and are called architected materials. Many studies have focused on developing approaches that allow hierarchical features of natural materials to be mimicked in completely different classes of material[5]. For example, one could generate a nacre-like material from synthetic polymers, rather than using the exact materials found in nacre.

Structures composed of repeating building blocks are commonly found in crystalline materials such as metals, ceramics and rocks. At the smallest scale, the atoms in crystals form a well-defined lattice in which the packing of atoms in the unit cell (the smallest repeating unit of the lattice) depends on the nature of the atoms' bonds and electronic structures. However, crystals are usually formed from microscopic grains whose lattices are oriented in different directions. If the configurations of atoms at the edges of different grains do not line up with one another, lattice defects form, which are commonly considered to be weak points. In brittle materials, cracks can be initiated from defects such as grain boundaries, and propagate rapidly.

But grain boundaries can have a positive role in ductile materials. Metals under a load typically fail not because bonds between atoms suddenly break, but because atoms slide along a specific plane within a lattice. Such sliding occurs as a result of defects known as

## 50 Years Ago

The collection of inventions that was on show … last week involved the onlooker in frantic changes of mood, switching his attention one minute to practical mechanical devices and the next to the thrills of psychedelic lighting or the niceties of tea blending … Among the household items was a flower pot designed to maintain a steady trickle of water in the gardener's absence, a new type of safety window for schools and hospitals, and for a wider audience a typewriter with keyboards in Japanese, musical notation or what you will.
**From *Nature* 18 January 1969**

## 100 Years Ago

The ex-President of the United States who died in the first week of 1919 was in many ways the most remarkable man … and combined with unusual qualities of intellect and co-ordinated development of bodily skill — for was he not a fine shot, a bold equestrian, an untiring marcher, an adept at most games and sports? — a kindness and sweetness of disposition, and a thoughtfulness for the happiness and well-being of all around him, very rare in great men of the world … Theodore Roosevelt was not only a great naturalist himself, but — what in its ultimate effect was even more important — he set, as President, the fashion in young America for preserving and studying fauna and flora until he had gone far to create a new phase of religion. Under his influence young men whose fathers and grandfathers had only studied the Bible, the sacred writings of the post-exilic Jews and Graeco-Syrian Christians, now realised that they had spread before them a far more wonderful Bible, the book of the earth itself. Geology, palaeontology, zoology, botany, ethnology, were part of Roosevelt's religion.
**From *Nature* 16 January 1919**

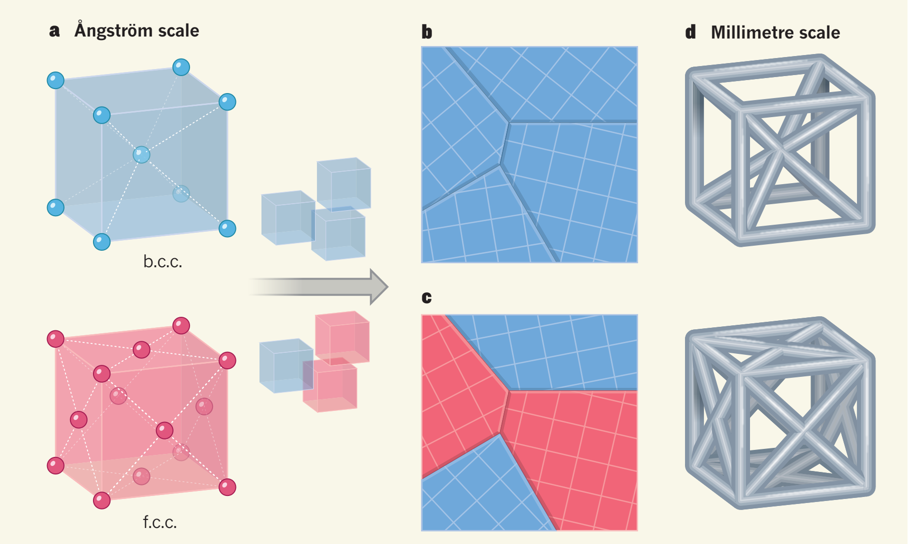

**Figure 1 | Two hardening mechanisms in polycrystalline materials.** **a**, The smallest repeating unit of a crystal lattice is called a unit cell. The body-centred cubic (b.c.c.) and face-centred cubic (f.c.c.) unit cells are commonly found in metals. **b**, Polycrystalline metals composed of only one type of unit cell typically contain microscopic grains, each of which has a different lattice orientation from that of surrounding grains. The boundaries between such grains can harden materials by preventing atoms from sliding along specific planes in the lattice. **c**, Multiphase materials contain domains built from different unit cells. This multiphase structure also hardens the material by preventing atom sliding. **d**, Pham *et al.*[1] report that the hardening mechanisms in **b** and **c** are also at work in architected materials built up from millimetre-scale f.c.c. and b.c.c. unit cells consisting of nodes (analogous to atoms) and struts (analogous to atomic bonds).

dislocations moving through the crystal lattice. This movement can be inhibited by grain boundaries, particles or precipitates (clusters of foreign atoms in the crystal lattice), because the sliding of atoms in a crystal becomes difficult if the array of atoms in a perfect crystal lattice is perturbed by such defects. The hindrance of dislocation movement therefore makes the material more resistant to deformation. A characteristic feature of polycrystalline metals is that their strength increases as grain size decreases[6]. This is because smaller grains allow less space for dislocations to travel freely. Similarly, the presence of multiphases (domains that have distinct mechanical properties) in grains can enhance strength because they also hinder dislocation movement[7].

Pham and colleagues investigated whether similar hardening mechanisms can be used to strengthen architected materials. They began by using additive manufacturing to construct millimetre-scale unit cells from nodes (analogous to atoms) and struts (analogous to atomic bonds), using various materials. The authors fabricated two types of unit cell, known as face-centred cubic (f.c.c.) and body-centred cubic (b.c.c.) structures (Fig. 1).

The researchers then assembled the unit cells in designs that replicated the defects and structures involved in hardening mechanisms in polycrystalline metals. For example, grain boundaries were simulated by misaligning grains in the architected materials (see Extended Data Fig. 5 of the paper[1]), and multiphase materials were reproduced by mixing f.c.c. assemblies with b.c.c. ones (Fig. 1). Fascinatingly, the authors observed that the same hardening mechanisms operating on the atomic scale in metals and alloys also strengthen architected materials on a larger scale. For instance, the orientation of grains in the architected materials determines the patterns of failure that occur in substructures, and the strength of the materials can be significantly improved by reducing the grain sizes.

Pham and colleagues' work provides further exciting evidence that architected materials can be used to construct multiscale structures such as fractal crystals[3]. Their approach could enable future research into the relationships between the characteristic length scales of substructures in conventional materials and the mechanical properties of those materials. More importantly, it suggests that architected materials could be used to study more-complex hierarchical structures, such as those of silk and bone, to work out which features are responsible for the structures' remarkable properties.

Future research should quantify how hardening mechanisms can improve the mechanical properties of architected materials, because this information will be essential for developing practical applications. Alternative methods for implementing precipitates and multiphases in architected materials should also be explored, along with the effects of using different constituent materials. The information obtained from experiments with architected materials might allow hardening mechanisms to be transferred from one conventional material to another, or from one scale to another, and this would help researchers to overcome the limitations of conventional engineering materials. Achieving such innovation will require a deep understanding of the fundamental failure mechanisms in existing materials from atomic to macroscopic scales, which can be facilitated using mathematical methods[5].

Pham and colleagues' study focuses mainly on compressive loading of materials, but future work should also examine other scenarios, such as extensional loading and the effects of impacts, or even the mechanical processes by which cracks propagate. Many other textbook principles of materials' properties could also be investigated using the authors' approach.

Studies of the effects of other types of unit cell might open up avenues of research aimed at developing architected materials that combine key features from different biomaterials. However, organizing geometric features such as grain sizes, multiphases and precipitates to produce a desired property will be tremendously difficult. Even for simple systems, the number of possible design combinations is extremely high, which would probably make it too costly to print and test each combination individually. Advances in theory and computational modelling will therefore be necessary for identifying the most promising designs for testing.

For instance, multiscale modelling based on the 'bottom-up' assembly of materials from the atomic scale or microscale might be crucial for understanding hardening mechanisms and optimizing structures to obtain desired materials properties. The combination of emerging modelling tools such as artificial intelligence and genetic algorithms might speed up efforts to understand the processes by which complex architected materials fail[8].

In the long run, if additive manufacturing can achieve the resolution needed to print atomic-scale structures, then the term 'architected material' might become obsolete as the concepts of structure and material become seamlessly integrated across all possible scales. Instead, we would enter a new era of personalized and printable designer materials. ■

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