Ordering the void

The metal alloys used as cladding for nuclear fission and fusion reactors must endure some of the most challenging engineering environments known. One of the problems they face is irradiation with high-energy products of nuclear reactions, which implant themselves in the metal matrix and can cause degradation and weakening. In particular, volatile elements such as helium (in fusion) and krypton and xenon (in fission) may diffuse through the lattice and gather into bubbles or voids, swelling and weakening the structure^{1,2}. In some fission reactor walls the swelling caused by voids can increase the volume by several tens of percent. Not only do the voids reduce the strength by making the metal a kind of foam, but also the volatile elements can migrate to and accumulate at grain boundaries, where they cause embrittlement.

It has been long known that these voids can become ordered into superlattices, recapitulating the symmetry of the crystal lattice (hexagonal or body-centred cubic, say) at scales orders of magnitude larger — that is, tens of nanometres². How this ordering arises hasn't been clear, although it has been proposed that it stems from a kind of repulsive interaction between the bubbles, perhaps caused by the patterns of dislocations they produce³. The ordering can in itself be good news for the alloy's mechanical properties, since it can sequester the insoluble gases away from grain boundaries and so reduce their embrittling effect.

A new proposal for the formation of void lattices in irradiated metals has now been put forward by Noble and colleagues⁴. Or rather, it is an old proposal in a new context, for the researchers suggest that the spontaneous pattern-forming process is basically that postulated in 1952 by mathematician Alan Turing⁵, which has been long suspected of creating a wide variety of patterns in nature — among them, animal markings⁶, shell

pigmentation patterns⁷ and structures in developmental biology⁸.

Turing's process generally involves the autocatalytic growth of pattern elements under the influence of diffusing 'morphogens'. One of these, called the activator, forms localized islands, while the other, called the inhibitor, suppresses the spread of the activator beyond those islands — leading to an effective repulsion between patches that organizes them into orderly arrays, typically of spots or stripes. Crucially, the activator and inhibitor must diffuse at different rates, the ratio of which determines the length scale of the patterning. In effect, their interactions trigger an instability of the uniform distribution of ingredients at the least stable wavelength.

Turing patterns have been seen in liquid-state chemical systems⁹, and are thought to be formed in animals by the diffusion of morphogens that control gene activity during embryogenesis. At first glance it would seem less obvious that they might arise in the solid state. But not only can impurities and defects migrate in metals — especially at high temperatures — but the activated, Arrhenius nature of that motion means that diffusion rates can be more markedly different than in solutions. Such disparities can create the conditions stipulated in Turing's theory.

Noble et al. describe calculations and simulations that provide a rather complete explanation of how void superlattices might arise this way in metals, due to the migration of both vacancies (empty lattice sites) and interstitials (atoms displaced from their usual positions in the lattice). They show that under certain conditions these elements can gather to form voids. If the diffusion rates of vacancies and interstitials do not differ too greatly, the voids grow by the mechanism of Ostwald ripening, whereby large ones grow at the expense of small

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ones. But for a greater disparity in diffusion rate, the opposite happens: large voids shrink and small ones grow until all have much the same size, and although they initially grow randomly, they become organized into a more or less ordered superlattice with (in this case) the same symmetry as the lattice (here hexagonal or body-centred cubic). This is predicted to occur only within a certain temperature window, just as empirically void superlattices are typically seen at around 0.2–0.4 times the metal's melting point.

Whether this does indeed explain the experimental observations remains, however, to be verified. If so, it's possible that the understanding might assist efforts to control the process so as to prolong the useful lifetime of irradiated metals in nuclear technology — and perhaps even permit its use to create designed nanostructured alloy materials.

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