Metallurgy

Fine-grained metals from 3D printing

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Conventional alloys have undesirably coarse-grained microstructures when used in 3D printing. A designer alloy overcomes this problem, potentially opening the way to the widespread adoption of 3D metal printing. **See p.91**

There are many potential benefits to using additive manufacturing — also known as 3D printing — for making metal parts, rather than conventional manufacturing processes. For example, additive manufacturing is highly customizable, it can produce complex structures and it can be used for the economical production of low numbers of metal components. But to achieve the strict specifications needed for some applications, the microscopic structure of printed metal objects must be controlled. On page 91, Zhang *et al.*[1] describe titanium–copper alloys that produce practically useful microscopic structures during additive manufacturing, removing the need for subsequent treatment. The resulting materials exhibit promising combinations of mechanical properties, comparable to those of the ubiquitous structural alloy Ti-6Al-4V, produced using conventional and additive manufacturing processes.

In metal additive manufacturing, an alloy (in the form of powders or wires) is deposited in a layer and then melted by a rapidly moving heat source to form a solid mass; successive layers are built up to produce a 3D part. The process typically produces large temperature gradients, high solidification rates and repeated cycles of heating and cooling. A common characteristic of 3D-printed metals is coarse columnar grains that grow along specific directions of the crystal lattice that are favourably oriented with the heat flow (Fig. 1a).

Coarse columnar grains are usually undesirable because they can cause the printed material to have direction-dependent (anisotropic) mechanical properties and make it susceptible to tearing or cracking during solidification[2–4]. However, columnar solidification can undergo a transition to equiaxed solidification — in which the grains produced have similar dimensions in all directions — by changing the processing conditions used for additive manufacturing[2]. Alloys with equiaxed grains have desirably uniform properties, and so methods for producing them are of great technological value[4].

Models and experiments have been used to study the columnar-to-equiaxed transition (CET) in nickel-based alloys that have been melted using an electron beam[2,3]. The number of nuclei (tiny crystals that ‘seed’ the growth of the solid phase) in the liquid metal, and the processing conditions used during electron-beam additive manufacturing, were found to have a larger influence on grain structure than did the composition of the alloy[3]. This suggests that the CET can be controlled through process design and by promoting nucleus formation in alloy melts. Additives called inoculants, which cause nuclei to form in the melt, have been incorporated into metal-alloy powders used in additive manufacturing, to increase the density of nuclei and thereby promote the formation of equiaxed grains[4]. However, suitable inoculants for titanium alloys remain elusive.

Zhang *et al.* now show that fine equiaxed grains, on average less than 10 micrometres in diameter, can be produced in titanium–copper alloys during additive manufacturing, without adding inoculants (Fig. 1b). The authors propose that nucleation and CET are promoted in these alloys by the formation of a large zone of supercooled liquid — melted alloy that is fully liquid, despite its being below the temperature at which the alloy should start to solidify. The final product consists of two solid phases that contain different amounts of titanium and copper, forming a microstructure that includes nanoscale plates (lamellae). The mechanical properties of the printed material compare favourably with those of Ti-6Al-4V, and of cast (and heat-treated) titanium–copper alloys.

The authors suggest that equiaxed grains are produced during solidification of the melt, and that further microstructural refinement might then occur during the cyclical

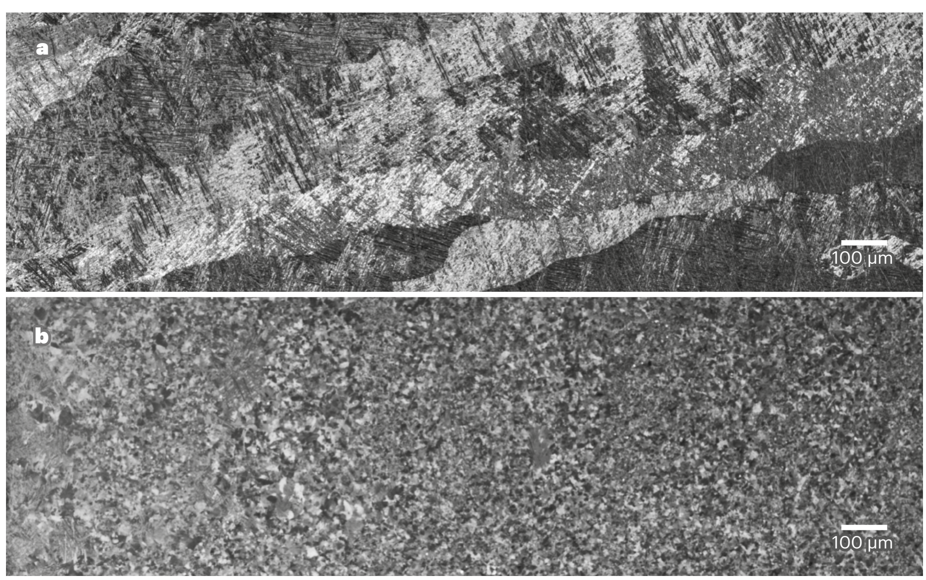

Figure 1 | Grain structure in printed metals. **a**, When conventional metal alloys are used for 3D printing, large columnar grains tend to form, as shown here for the structural alloy Ti-6Al-4V. This causes the printed alloy to have undesirable anisotropic (direction-dependent) properties. **b**, Zhang *et al.*[1] report that titanium–copper alloys produced by 3D printing contain fine grains that have similar dimensions in all directions. The alloy shown here was produced using the same conditions as in **a**. (Images from ref. 1.)

temperature changes associated with the 3D-printing process. However, it is difficult to tell unambiguously whether the solidification step is the genesis of the fine grains, because the microstructures produced at high temperatures during solidification will be replaced by features that develop during subsequent solid-state phase transitions. Another plausible scenario is that columnar grains form during solidification, and that equiaxed grains are produced and refined during solid-state thermal cycling. Such grain refinement has been reported in steels[5].

When steels that have a two-phase lamellar microstructure at low temperatures are heated above a critical temperature, new grains of a third phase (austenite) nucleate and grow. The two low-temperature phases then re-form on cooling[5]. Repeated nucleation and growth of the various phases can therefore occur under suitable conditions during thermal cycling, leading to significant grain refinement.

Alloys such as Ti-6Al-4V typically do not undergo grain refinement during thermal cycling[6], because no new grains of the high-temperature phase nucleate. However, it is unclear whether new grains of high-temperature phase can nucleate and grow in Ti-6Al-4V during thermal cycling typical of additive manufacturing[7], which might conceivably refine grains. Zhang and colleagues' titanium–copper alloys have high- and low-temperature phases analogous to those of steels. Clarifying the role of nucleation and growth of these phases in grain refinement during thermal cycling should be a topic of future research.

A deeper understanding of solidification and solid-state phase transitions is clearly needed to guide the design of future alloys for additive manufacturing and to control their microstructures – although the nucleation stage is hard to study experimentally. It is also imperative that we have a better understanding of how the rapidly changing conditions during additive manufacturing influence microstructure development. *In situ* characterization of phase transitions and dynamic phenomena, for example using imaging and diffraction techniques in experiments that simulate the conditions of additive manufacturing[8,9], might help to unveil some of the complexity of the processes involved. Such efforts are timely, and are necessary to produce optimized alloys that will lead to the widespread adoption of additive manufacturing for the production of high-performance structural parts, for which reliably high-quality microstructures and mechanical properties are of the utmost importance.

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Neuroscience

The fruit fly gets oriented

Malcolm G. Campbell & Lisa M. Giocomo

Two studies in flies reveal the mechanism by which the brain's directional system learns to align information about self-orientation with environmental landmarks – a process crucial for accurate navigation. **See p.121 & p.126**

As everyone knows, a good sense of direction is needed to successfully navigate the world. In mammals, this 'sense' involves neurons called head-direction cells. Each such cell becomes most active when the animal faces a particular direction relative to landmarks in its environment. Together, the cells' activity indicates which direction the animal is facing in at any given moment. In 2015, it emerged that fruit flies, which are much easier than mammals to study experimentally, have strikingly similar cells, called heading neurons[1]. Fisher *et al.*[2] (page 121) and Kim *et al.*[3] (page 126) now build on this discovery to tackle a decades-old problem: how does this type of neuron respond to the locations of landmarks in a manner that is stable enough to be reliable, but flexible enough to allow adaptation to new environments?

"This shows that the fly's heading network can store and retrieve memories of scenes."

To give an example of the problem, imagine emerging from a subway station onto a crowded street. If you are a regular visitor, a glance around is all you need to be on your way. However, if you have never been to this station before, you might need a moment to orient yourself. You take note of surrounding street signs, shops and monuments. Before long, you have your bearings and can set off in the right direction.

This example highlights two challenges for the brain's directional system. First, it must stably indicate direction in familiar environments: returning to the same station should call the same orientation to mind. Second, it must have the flexibility to learn new configurations of landmarks, even when similar landmarks have been seen before – the particular configuration of street signs at the new station must be learnt, even though you may have seen similar street signs in other places.

The neural mechanisms that underlie these abilities in flies are a beautiful example of form following function. The insects' heading neurons (also known as E–PG, or compass, neurons) are arranged in a ring (Fig. 1) that corresponds to the 360° of possible directions in which the fly can face[1], sometimes called heading angles. Because of inhibition between neurons, only one heading angle can be indicated at one time, providing the fly with an unambiguous signal. Of note, rather than always aligning their activity to a cardinal direction such as north, heading neurons realign their activity arbitrarily when the fly enters a new environment. The heading neurons receive input from visual ring neurons, which are activated by visual cues at particular orientations relative to the fly, and from internal cues about self-motion.

Fisher *et al.* set out to test whether and how the connections between visual ring neurons and heading neurons change with experience, using a range of experimental techniques (many of which are possible only in fruit flies). They implemented a virtual-reality (VR) system in which the fly walked on a floating ball. An array of lights around the fly flashed on and off in concert with the animal's movements[4], providing visual cues to enable the fly to orient itself. The authors then measured inputs from visual ring neurons to heading neurons as the flies explored this virtual environment. They also used genetic techniques to inhibit the activity of visual ring neurons.

These experiments revealed that individual heading neurons are inhibited by visual ring neurons that are activated by visual cues at specific angles relative to the fly. Because of the specificity of this pairing, the visual input