Materials science

High-resolution 3D printing in seconds

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A 3D-printing technique has been developed that can produce millimetre- to centimetre-scale objects with micrometre-scale features. It relies on chemical reactions triggered by the intersection of two light beams. **See p.620**

In the *Star Trek* universe, devices called replicators can manifest solid matter in seconds. Thanks to advances in materials science, these science-fiction devices might be closer to reality than we think. A type of 3D printing called volumetric additive manufacturing (VAM) uses light to rapidly solidify an object in a volume of a liquid precursor. On page 620, Regehly *et al.*[1] report an advance in VAM that allows solid objects to be printed with a feature resolution of up to 25 micrometres and a solidification rate of up to 55 cubic millimetres per second. The authors call this process xolography because it uses two crossing (x) light beams of different wavelengths to solidify a whole object (*holos* is the Greek word for whole).

Conventional 3D printers have gantries that manoeuvre either the printheads or the printed object in three orthogonal directions to orient the printer's nozzle to the next position to deposit material. However, the fastest 3D printers use light to induce the polymerization of an entire layer of a liquid starting material at a time, thereby allowing solid objects to be drawn out from the liquid with rates of 500 millimetres per hour (ref. 2). If the light flux and polymerization kinetics are tuned properly, the printed object is monolithic – it has none of the artefacts that could be produced by the layer-by-layer printing process. VAM removes the need to draw an object out from the starting material, simplifying the mechanics of the process and allowing even faster fabrication. It also enables the production of higher-quality parts than is possible with other methods, and it removes the need to print support structures for the object that must then be removed after printing.

Previous variants of VAM included two-photon photopolymerization (TPP)[3,4] and computed axial lithography (CAL)[5,6]. In TPP, femtosecond laser pulses (1 femtosecond is 10^{-15} seconds) are used to polymerize nanoscale building blocks, which can be layered to fabricate microstructures. TPP is slow, with a printing rate of just 1–20 cubic millimetres per hour, and is typically used to make millimetre-scale objects, but it can print features at a resolution of 100 nanometres.

By contrast, CAL moved the abilities of VAM in the other direction by allowing high-speed solidification of centimetre-scale objects. In CAL, images are projected at different angles around a rotating volume of a liquid precursor, using algorithms to control the cumulative light exposure at different voxels (3D pixels). This is done in concert with a system that uses dissolved oxygen to prevent free-radical species from initiating unwanted polymerization, so only the volumes of interest are solidified. CAL can achieve feature sizes of 100 micrometres and fabricate centimetre-scale parts in just seconds, but it requires computer optimization using a feedback system, which adds to the cost of the equipment and the total printing time.

Regehly and colleagues report new chemistry for initiating polymerization in VAM that better controls the volume of liquid in which initiation and polymerization occur. Their technique increases the resolution to up to ten times that of previously reported macroscopic VAM techniques, without sacrificing the printing rate.

The xolography process works as follows. A rectangular sheet of light with a set thickness is shone through a volume of a viscous resin (Fig. 1). The wavelength of the light is chosen to excite molecules known as dual-colour photoinitiators (DCPIs) dissolved in the resin by cleaving a molecular ring in the backbone of the molecule; this reaction occurs only within the sheet of light.

A second beam of light projects an image of a slice of the 3D object to be printed into the plane of the light sheet. The wavelength of the second beam is different from that of the first and causes any excited DCPI molecules to initiate polymerization of the resin, solidifying the slice. The resin volume is then moved relative to the position of the light sheet, which is fixed. This changes the position of the light sheet in the resin, so the activation and initiation processes can begin again at a new position, thereby building up the object slice by slice.

The authors demonstrated the effectiveness of their technique by printing a ball trapped as a loose object in a spherical cage, which was 8 millimetres in diameter (Fig. 2). Using conventional layer-by-layer 3D printing, the ball would have needed to have been printed with supports connecting it to the cage, and they would have been difficult to remove afterwards. The high resolution afforded by xolography also allows it to print mechanical

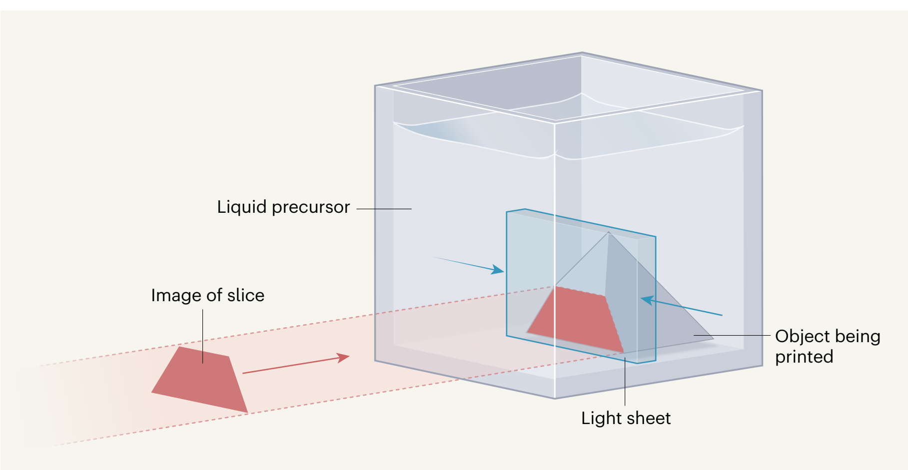

Figure 1 | A method for high-resolution 3D printing. Regehly *et al.*[1] report a technique called xolography, which uses light to solidify objects from a liquid precursor. A rectangular sheet of light (blue) is shone through a volume of a viscous resin, and activates molecules known as dual-colour photoinitiators (DCPIs, not shown) dissolved in the resin. A second beam of light (red) then projects an image of a slice of the object to be printed into the plane of the light sheet. The wavelength of the second beam is different from that of the first, and causes any activated DCPIs to initiate polymerization of the resin, solidifying the resin where the two wavelengths of light cross. The light sheet is then moved to a new position by shifting the resin volume on a linear stage, and the process begins again, building up the object slice by slice.

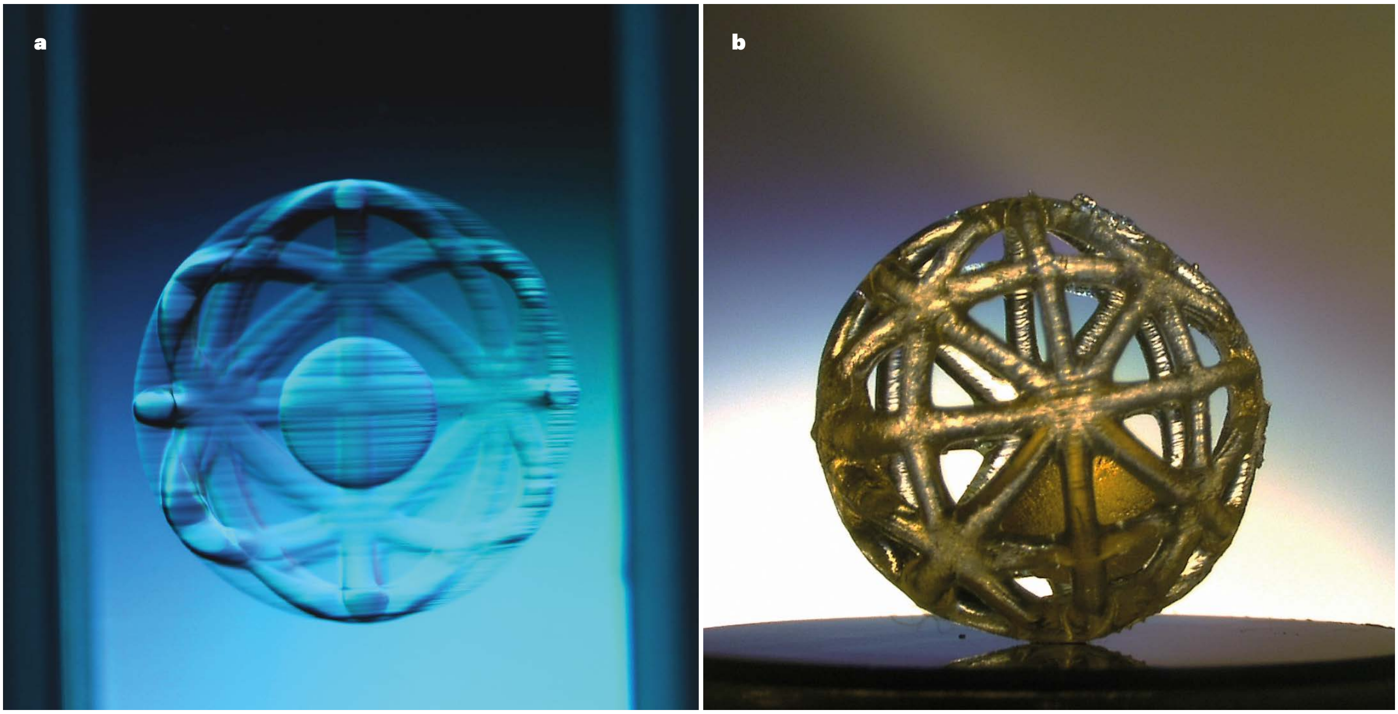

Figure 2 | A complex object produced by xolography. Regehly and colleagues have used xolography to print several complex objects with high feature resolution, including a ball trapped as a loose object in a spherical cage. Such objects are often difficult to print directly using conventional 3D-printing processes. These images show the object as it is being printed (**a**) and after processing (**b**). Cage diameter, 8 millimetres.

systems directly, such as blades that can spin on an axle in a flow of liquid or air (see Fig. 2d–f of the paper[1]).

In an even more ambitious demonstration, Regehly *et al.* used xolography to print an aspherical Powell lens (see Fig. 2g–i of the paper) — a type of lens used to convert laser beams into straight, uniform lines of light. In air, the lens stretched a narrow green laser beam into a projected straight line. The optical properties of the lens demonstrate that the structure of the printed material is remarkably uniform and free from defects. Finally, the authors printed a highly detailed 3-cm-diameter bust of a person, with precisely defined internal anatomical features, such as a hollowed-out nasal passage and oesophagus (see Fig. 2j–l of the paper).

Currently, the major limitation of xolography is the volume that can be printed, because this is restricted by the distance the light beams can penetrate into the resin. Moreover, because the method requires the resin volume to be moved, objects with large dimensions in the direction of movement will take proportionally more time to make than shorter ones. And although the reported chemistry enables high-resolution printing, it also limits the materials that can be used for xolography.

Despite these limitations, the future holds many possibilities for xolography, and for other VAM methods in general. Techniques similar to those pioneered for digital light processing (DLP, a conventional layer-by-layer 3D-printing method in which solidification is initiated by light) could now be applied to VAM. For example, greyscale illumination could be used to fabricate objects with gradients of stiffness. This would find many applications, such as toughening the interfaces between different 3D-printed components, and in unusual engineering mechanisms such as living hinges (flexible joints formed from the same material as the rigid pieces they connect).

Regehly *et al.* predict that the feature resolution and volume-generation rate of xolography could be enhanced further by using better optical systems, such as more powerful lasers. But some challenges remain for all VAM systems, such as scaling up printing volumes from cubic centimetres to cubic metres, and finding ways to use multiple materials in the same print.

“The high resolution afforded by xolography also allows it to print mechanical systems directly.”

The advent of improved printing speeds and new materials has allowed a DLP method to be used for the mass customization of midsoles for running shoes, as part of a product-development process (see go.nature.com/3gy86wp). If similar advances can be made using VAM and xolography, this might enable the mass production of commercial products. Other opportunities, including applications that are not yet possible using 3D printing, are sure to be in the offing. As Regehly and colleagues' work shows, it is truly an exciting time for this field.

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