4D printing for future manufacturing

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Additive manufacturing (AM), also called 3D printing, offers disruptive design freedom and manufacturing flexibility due to the layer-wise incremental formation manner of components. Advancements in AM techniques provide unique advantages and feasibilities for overcoming challenges arising from fabricating parts with complexities in geometry, materials, and properties. 4D printing has been recognized as an advanced AM technique, providing more opportunities for creating components with more noticeable functionality. Unlike primary 3D printing techniques, which create three-dimensional objects with permanent shapes, 4D printing uses similar AM techniques to create objects with an extra transformation process over time. The classic concept terms 4D printing as: the shape, property, or functionality of a 3D printed structure that can change as a function of time when subjected to environmental stimuli, including but not limited to heat, light, water, electric energy, pH change, etc. [1].

Current mainstream investigations on 4D printing can be considered ***ex-situ*** **4D printing** since the time-dependent evolutions occur after 3D objective formation rather than synchronously [2]. AM of shape memory materials (as summarized in Figure 1a) is the most prevalent format of ex-situ 4D printing. For instance, the AM-printed shape memory alloys display shape recovery when subjected to heating, in which the shape change occurs after object printing. Similarly, in the 4D bio-printed functional folding flower architectures, the shape transformation stimulated by water also happens after construct printing is completed [3]. Specifically, the constructs printed by direct writing of viscoelastic composite ink contain spanning filaments, and the inter-filament spacing promotes rapid uptake of water via the micron filament radius, which leads to shape transformations like flower closing (see Figure 1b).

4D printing can not only be accomplished via the shape change of components through external stimuli, but also can be achieved through the internal microstructure change during

AM. Recent work by Tan *et al.* [4] highlights ***in-situ* 4D printing** of novel high-strength steel via in-situ integration of time-dependent precipitation evolution with 3D geometry shaping during laser-directed energy deposition (LDED), as illustrated in Figure 1c. The novel high-strength steel customized by machine learning has fast precipitation kinetics and high peak precipitation density, enabling the formation of precipitates within a short time. Meanwhile, the intrinsic heat treatment (IHT) effect on the solidified materials during LDED, which originates from the unique cyclic thermal history, leads to the in-situ formation of many Ni_3Ti precipitates in the high-density dislocation martensitic matrix in as-built condition (without heat treatment).

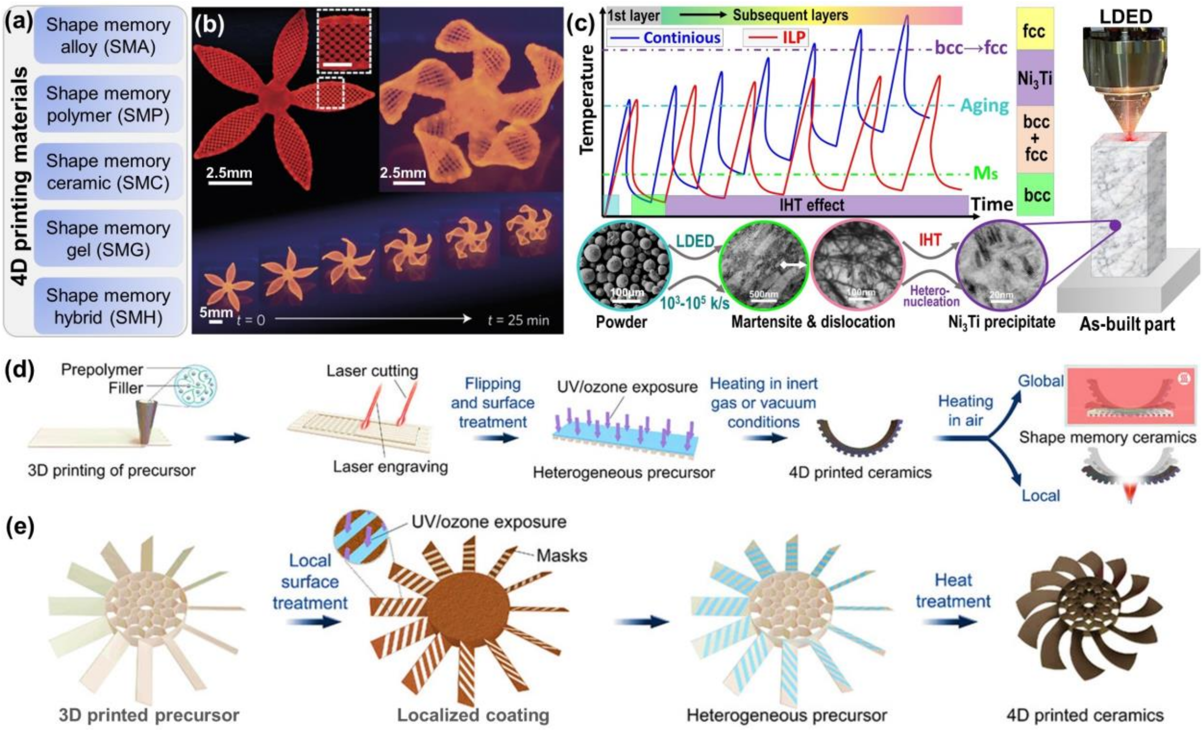

Figure 1. Materials and methodologies of 4D printing. (a) Shape memory materials for 4D printing, (b) 4D printed complex flower morphologies mimicked biomimetic shape transformation based on the anisotropic alignment of fibrils within the structure (with time-lapse sequences of the flowers during the swelling process) [3], (c) in-situ 4D printing of high-strength steel via in-situ integration of time-dependent precipitation evolution with 3D geometry shaping (ILP stands for interlayer pause deposition strategy) [4], (d) schematic of hybrid 4D printing by combining and additive and subtractive manufacturing and (e) its potential application in manufacturing ceramic engine turbine disk [5].

Apart from existing in-situ and ex-situ 4D printing technologies, a recent work by Liu *et al.* [5] developed a new type of 4D printing, which can be categorized as hybrid 4D printing as it combined direct ink writing (DIW) additive manufacturing with laser machining subtractive manufacturing. As shown in Figure 1d, during this hybrid 4D printing, the DIW was used to form elastomeric ceramic precursors, while the laser machining technique was used to engrave or cut high-resolution features to tune the structure stiffness of the component. A coating with tuneable thickness and graded stiffness was subsequently created on the surface of the laser machined precursors by an ultraviolet (UV) ozone generator. When the as-built samples were subjected to heat treatment, the thermal expansion and shrinkage behaviours of the ozone-coated regions and precursor material were different; this heterogeneity in the thermal expansion-shrinkage behaviour led to a shape transformation of printed structures, which differentiates from the typical shape transformation mechanism in shape memory ceramics (SMCs) via martensitic phase transformations [6]. This hybrid 4D printing strategy shows potential capabilities in producing hard-to-manufacturing components such as the ceramic engine turbine disk, as illustrated in Figure 1e. Current results indicate this hybrid 4D printing technique could address various challenges (e.g., geometrical flexibility, manufacturing precision, and shape memory capability) in developing SMCs despite the drawback of cumbersome processes.

The newly developed hybrid 4D printing technique highlighted the advancement of processing technologies. However, 4D printing is a multidisciplinary technology, and there needs collaborative innovations in time-dependent transformation mechanisms, process technologies and materials to further advance 4D printing. It is worth pointing out that many time-dependent transformation mechanisms could be inspired by natural structure-forming processes like the heliotropism of sunflowers, as learning from nature can discover new ways to solve technical bottlenecks [7, 8]. Moreover, rapidly developed artificial intelligence techniques like machine learning will be essential in discovering novel materials and structures suitable for future 4D printing.

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