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From Static to Dynamic: The Transition from 3D to 4D Ceramic Printing

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Abstract

4D printing represents a phenomenal shift in additive manufacturing, introducing programmable transformation over time when exposed to specific external stimuli (such as heat, light, moisture, or magnetic fields), contrasting with traditionally static 3D-printed objects. This research explores the evolution from 3D to 4D ceramic printing, emphasising the integration of smart materials and stimuli-responsive behaviours to make self-transforming structures. Unlike traditional 3D printing, which produces complex, rigid objects, particularly in ceramics, 4D printing integrates dynamic functionality directly into materials, enabling printed structures to change shape, properties, or functionality after fabrication. This overcomes the limitations in post-production adaptability in 3D printing, significantly changing the concept of layer-by-layer building and enhancing traditional ceramic properties like high hardness, compressive strength, and low brittleness. This is achieved through the development of smart integrated materials such as shape-memory polymers, ceramic ink, elastomeric nanocomposites, elastomeric precursors and hydrogel-driven dehydration polymers, which allow for complex, high-strength ceramic structures through techniques like origami folding and hydrogel-assisted morphing and facilitate dynamic shape morphing in response to environmental stimuli. The research demonstrates a radical shift in ceramic additive manufacturing to 4D printing, expanding applications in biomedical, aerospace, and electronics fields. Despite its potential, 4D ceramic printing faces barriers such as material costs, design complexity, and scalability challenges. However, its energy efficiency, sustainability, and unique ability to merge structural durability with dynamic functionality position it as an advanced technology. This study highlights the shift from static fabrication to responsive manufacturing, confirming crucial future directions for smart material integration and widespread industry implementation.

Keywords

4D Printing, Additive Manufacturing (3D Printing), Ceramics, Smart Materials.

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Introduction:

4D printing is an advanced additive manufacturing technology that creates multi-material objects able to transform over time when exposed to specific external stimuli (such as heat, light, moisture, or magnetic fields). Unlike traditional 3D printing, which produces static objects, 4D printing embeds dynamic functionality directly into materials, enabling printed structures to change shape, properties, or functionality after fabrication independently, emphasising that printed structures are no longer simply static, dead objects; rather, they are programmable active and can transform independently. 4D Printing is a new process that demonstrates an outstanding shift in additive manufacturing. (Tibbits, Skylar. 2014, P. 119)

Research Problem :

The primary research problem addressed in this study is the limitations of traditional 3D ceramic printing, which produces static, rigid structures with poor post-production adaptability. 3D printing lacks the ability for objects to change or adapt after fabrication, especially challenging for ceramics with their high firing temperatures and difficulty in moulding/deforming post-printing. Ceramics, despite their high strength and thermal stability, are brittle and difficult to shape using conventional methods. The transition to 4D printing aims to overcome these challenges by integrating smart materials that enable dynamic, stimuli-responsive transformations.

Research Objectives:

This research aims to investigate the transition from 3D to 4D ceramic printing while addressing key challenges in ceramic 4D printing and exploring the integration of smart materials in 4D printing.

Research Significance: The significance of this research lies in introducing 4D capabilities to ceramics, merging structural durability with dynamic functionality, and expanding applications

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beyond static 3D-printed objects. Overcoming material limitations specifically for ceramics, the research shows how 4D printing can overcome challenges like brittleness and poor deformability, allowing for the creation of complex, high-strength ceramic structures.

Research hypotheses:

The static nature of 3D-printed ceramics often results in traditional ceramic processing limitations, including brittleness and difficulty in deformation. 4D printing can overcome these challenges by integrating smart materials and enabling material adaptability, it allows ceramic structures to exhibit programmable transformation (in shape, properties, or functionality) in response to external stimuli.

Research methodology:

The methodology employs case studies of ceramic 4D printing paradigms to overcome limitations in post-production adaptability of 3D printing by utilising advanced 4D printing ceramic materials, enabling dynamic shape-morphing capabilities and enhanced functionality in response to environmental stimuli.

Theoretical Framework

1- Differences of 3D printing and 4D Printing:

Additive manufacturing (AM), commonly known as three-dimensional (3D) printing, is a popular fabrication technique due to its ability to create complex, customizable structures from a 3D computer-aided design (CAD) file. It is an attractive alternative to traditional fabrication processes (e.g., moulding and machining) due to the reduction in both difficulty and cost of producing detailed, customizable products. Developments since the introduction of 3D printing in 1984 have included improved fabrication accuracy, speed, multiple materials, and costs. However, a fundamental flaw of these structures is their static and rigid nature, retaining the shape in which they were originally printed and generally only performing one function, 3D printing is an additive manufacturing technique that creates complex, customized static objects from digital designs. While it offers advantages over traditional methods, its products lack the ability to change after fabrication.

The drive to incorporate active materials into the 3D printing process to overcome these limitations has led to the development of four-dimensional (4D) printing technologies to create dynamic structures. 4D printing is the fabrication process of 3D objects that can change their shape over time or in response to an environmental stimulus.

It offers a streamlined path from idea to reality with performance-driven functionality built directly into the materials. With this technique, a wide range of active programmable materials can be produced, which can self-transform from one shape to another.

Systems that respond independently to a change in their environment are commonly found in nature; for example, the nastic movement of leaves and flowers can be triggered by humidity, light, or touch. This property had not, however, yet been achieved in manufactured objects until recently, 4D printing methods using smart materials to produce four-dimensional structure with metamaterials. These three-dimensional structures are dynamic and can self-transform in response to a predetermined environmental stimulus, such as electricity, light, temperature, or moisture, hence creating a fourth dimension of time. The shape-changing characteristics of these structures derive from the use of stimuli-responsive smart materials during the printing process, which give the structure the ability to change its function, shape, or physical properties, such as Young’s modulus, to form selective structures and configurations. (Bajpai, Ankur,… 2020, P. [1:2)

Diagram 1. 4D printing combines smart materials to create structures with new functionalities while 3D printing uses traditional materials to produce static structures. (Net 1)

Table 1. Key Differences Between 3D Printing and 4D Printing: Features, Materials, and Applications (Bajpai, Ankur,… 2020, P. 2)

Characteristics	3D Printing	4D Printing
Build Process	Structure formed by sequential layering of 2D material	Extension of 3D printing with shape-memory programming step
Materials	Thermoplastics, ceramics, metals, biomaterials, nanomaterials	Smart materials: shape-memory polymers (SMP), shape-memory alloys (SMA), hydrogel composites, biomaterials
Shape Flexibility	Creates rigid structure	Characteristics of structure change upon exposure to external stimulus
Shape-Memory Programming	No programming step	Thermomechanical training, multi-material printing to create differential stresses
Application	Medicine, engineering, dentistry, automotive, robotics, fashion, aerospace, defense etc.	Adds dynamic element to all 3D printing applications
Design Approach	Geometric modeling	Multi-material + stimuli-responsive programming

2- 4D Printing Strengths and Limitations:

Adopting 4D printing can lead to savings in energy, materials, time, and money. Furthermore, it can help reduce waste, errors, and product loss in manufacturing. Studies have also described the 4D printing process as energy-efficient, sustainable, and rapid compared to other production methods. 3D printing is the process of creating an object, while 4D printing involves a more creative approach, such as altering the object's structure or making it move after printing. 4D printing is seen as a strong competitor for example in creating biomedical scaffolds because these printed objects can react to changes in the body's environment. Its versatility, sensitivity, and advanced design and stimulation features suggest it could be the next step in producing microrobots. Furthermore, 4D printing allows programming to be directly incorporated into a material itself, without needing external devices.

Similar to 3D printing, 4D printing may has some of its limitations. Designing for 4D printing is more intricate than for 3D printing due to the added complexity of incorporating mechanically changing behaviours into the printed objects. Given its relatively recent development, 4D printing currently has a limited amount of established research. It has been noted that 4D printing using shape-memory materials is still in its early stages of development compared to 3D printing. However, 4D printing technology has introduced several alternative smart materials. A challenge with 4D printing is ensuring accuracy because of variations in optimizing parameters to control size and shape functionality. (Aldawood, Faisal Khaled. (2023), P. [3:4])

Table 2. Pros and Cons of 4D Printing Across Key Aspects

Aspect	Advantages	Disadvantages
Functionality	-Self-assembling structures reduce manual labor. -Adaptive properties (e.g., shape-memory, self-repair).	-Limited control over transformation timing/accuracy. -Complex programming required.
Materials	-Smart materials (polymers, hydrogels, alloys) enable dynamic responses. -Biomimicry allows nature-inspired designs.	-High cost of shape-memory/responsive materials -Limited durability in some environments.
Applications	-Biomedical (self-adjusting stents, drug delivery). -Aerospace (morphing wings, self-repairing parts). -Sustainable infrastructure (adaptive buildings)	-Specialized Applications; not yet common.
Sustainability	-Reduces waste via optimized material use. -Energy-efficient structures (e.g., passive cooling).	-Some smart materials are non-recyclable. -Energy-intensive stimuli (e.g., heat/light requirements).
Cost & Scalability	-Potential long-term savings in manufacturing/ assembly.	-High R&D and prototyping costs. -Difficult to mass-produce.
Precision & Reliability	-Customizable for complex geometries. • Responsive to environmental changes.	-Unpredictable deformations in some conditions. • Limited repeatability in transformations.

3- 4D printing Process:

Different 3D printing technologies exist, and their processes vary. A variety of materials, such as shape-memory materials, metamaterials, self-healing materials, polymers, metals, and nanocomposites, can be used in both 3D and 4D printing. However, materials with lower strength and stiffness are often preferred for 4D printing. Notably, materials for 4D printing need to respond in real-time, react to multiple environmental states, be intelligent, have a predictable response, and exhibit a local response to stimuli.

3.1. Shape Transformation Paradigms in 4D Printing

4D printed structures demonstrate remarkable shape-shifting capabilities across dimensional transformations, including:

- 1D to 1D: Linear expansion and contraction
- 1D to 2D: Folding and bending from linear to planar configurations
- 1D to 3D: Complex folding from linear to volumetric forms
- 2D to 2D: In-plane bending deformations
- 2D to 3D: Morphological transformations through:
  - Bending
  - Folding
  - Twisting
  - Surface curling
  - Topographical surface changes
  - Combined bending and twisting
- **3D to 3D: Volumetric shape changes including:**
  - Bending deformations
  - Linear deformations
  - Nonlinear deformations (Mahmood, Ayyaz, …2022, P. [2:6])

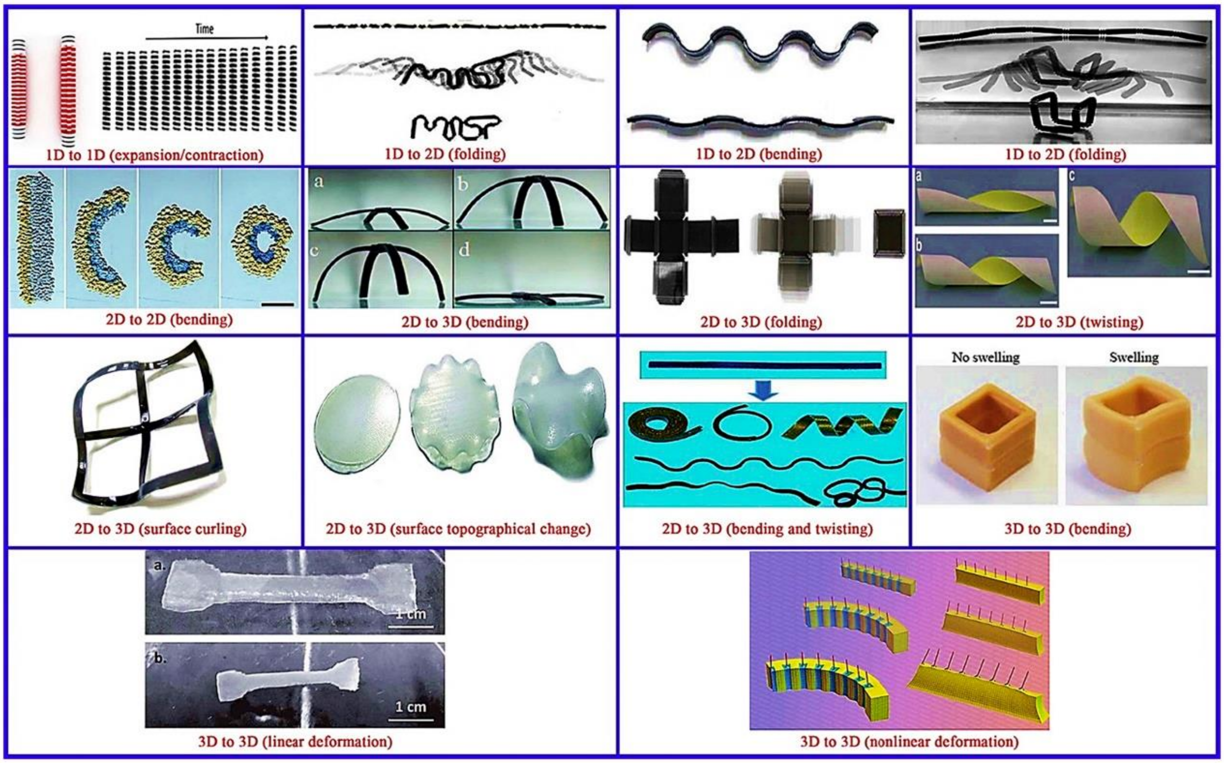

Figure1. Various examples of different kinds of shape Transformation responses in 4D Printing (Mahmood, Ayyaz, …2022, P. [2:6])

These transformation mechanisms enable sophisticated functionality in 4D printed materials, with applications ranging from biomedical devices to adaptive architectural components. The dimensional transitions are achieved through careful material selection and structural design, allowing precise control over the transformation pathways and final configurations. (Mahmood, Ayyaz, …2022, P. [2:6])

4- 4D printing Materials Properties:

In 3D printing, due to recent developments, materials have been able to be more precise and flexible, which has helped a great cause in 4D printing. The materials used for 4D printing are generally called Smart Materials as they change their properties over time. These materials can respond to the external stimulus and possess behaviours like self-assembly, self-healing, shape memory, and self-capability. 4D printing not only uses materials capable of shape change but also produces colour change when exposed to UV and visible light.

The fundamental distinction from 3D printing lies in 4D printing’s dynamic functionality, where material selection and transformation methods can be precisely tailored to application-specific requirements. This represents a paradigm shift from static, single-material 3D printing to adaptive, multi-material systems properties:

- Self-assembly: Structures can autonomously reconfigure into target geometries
- Self-adaptability: Continuous environmental responsiveness enables dynamic functionality
- Self-repair: Damage control via a material's properties.

These capabilities enable groundbreaking applications such as:

- Biomedical devices that navigate through the body and assemble at target sites.
- Adaptive infrastructure that responds to environmental conditions.
- Robotic systems with embodied intelligence for complex tasks. (Mallakpour, Shadpour,, 2021, [4:7])

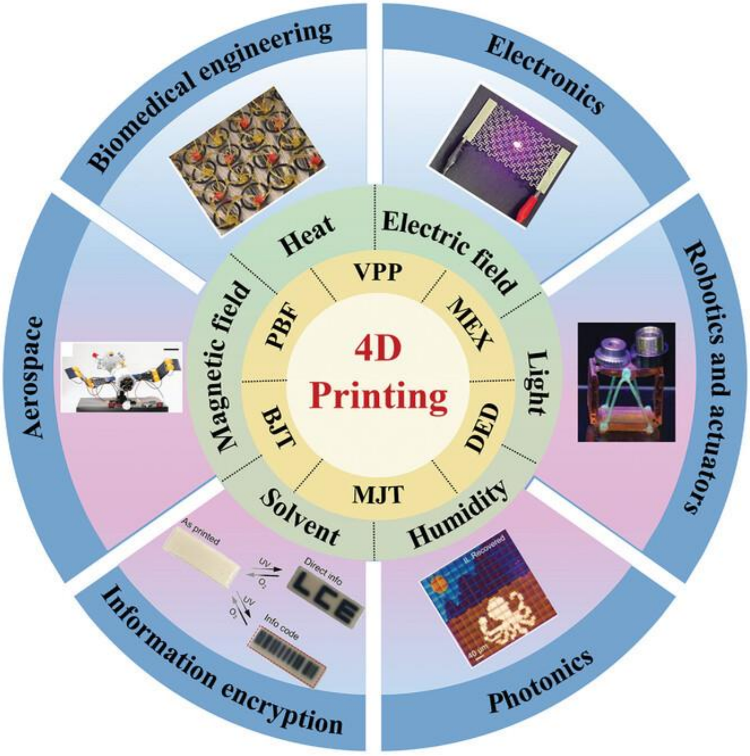

Figure 2. 4D Printing: Technologies, Activating Stimuli, and Practical Applications. (Wan, Xue, 2024)

5- 4D printing in Ceramics:

Ceramics are utilized in powder-based additive manufacturing, offering high strength, hardness, and stability, making them adaptable for 3D printing. Shaping typically involves powder mixtures. However, ceramic 3D printing is more difficult than with polymers or metals due to high melting points and feedstock preparation. Various techniques are used to create ceramic structures, but many suffer from porosity and cracks, which weaken the final product. Two alternative methods for creating ceramic structures exist. One involves coating 3D-printed polymer templates with ceramic films using atomic layer deposition, which can produce intricate nano/micro-structures after removing the polymer. However, this method is limited by the small scale of the structures and slow production. The second approach uses polymeric precursors, where printed polymers are transformed into ceramics with minimal shrinkage. This method allows for complex designs and is more energy-efficient than traditional sintering. (Mahmood, Ayyaz, 2022, P. [10])

4D printing, which combines 3D printing with a shape-morphing step, allows for more intricate shapes than standard 3D printing. However, deforming 3D-printed ceramic precursors is typically challenging, limiting 4D ceramic printing. To address this, elastomeric nanocomposites were developed that can be printed, deformed, and then converted into silicon oxycarbide nanocomposites, enabling complex ceramic origami and 4D structures. These ceramic precursors are soft and highly stretchable. This method allows for hierarchical ceramic structures across different scales and achieves high compressive strength. This work opens new possibilities for printing high-resolution, strong ceramics and offers a time-efficient approach due to the flexibility of the precursors. The shape-morphing capabilities of these elastomer-derived ceramics could be valuable for autonomous morphing structures, aerospace components, space exploration, electronics, and high-temperature microelectromechanical systems.

Additive manufacturing (AM) of ceramic precursors has revolutionized the production of complex ceramic structures through techniques like coating film-based ceramics and polymeric precursor-based ceramics (PPC). Atomic layer deposition enables the creation of hollow ceramic nanolattices by coating 3D-printed polymer templates (e.g., with TiN or Al_2O_3), though their microscale size and slow manufacturing limit applications. Alternatively, preceramic polymers, particularly silicon-containing polymers (yielding SiCNO, SiOC, or SiCN ceramics), allow intricate structures via polymer-derived ceramics (PDCs) with minimal shrinkage and lower energy use than traditional sintering. PDC nanocomposites, enhanced by nanofillers, improve mechanical strength, making them vital for structural and functional applications. Recently, 4D-printed ceramics were achieved using elastomeric poly(dimethylsiloxane) nanocomposites, enabling shape-morphing into silicon oxycarbide ceramics via pre-strained precursors—opening possibilities for ceramic origami and hybrid soft/rigid materials in bio-implants and bio-inspired designs. These advances highlight the transformative potential of AM in ceramics, combining precision, energy efficiency, and dynamic functionality. (Liu, Guo, 2018, P. [10:11])

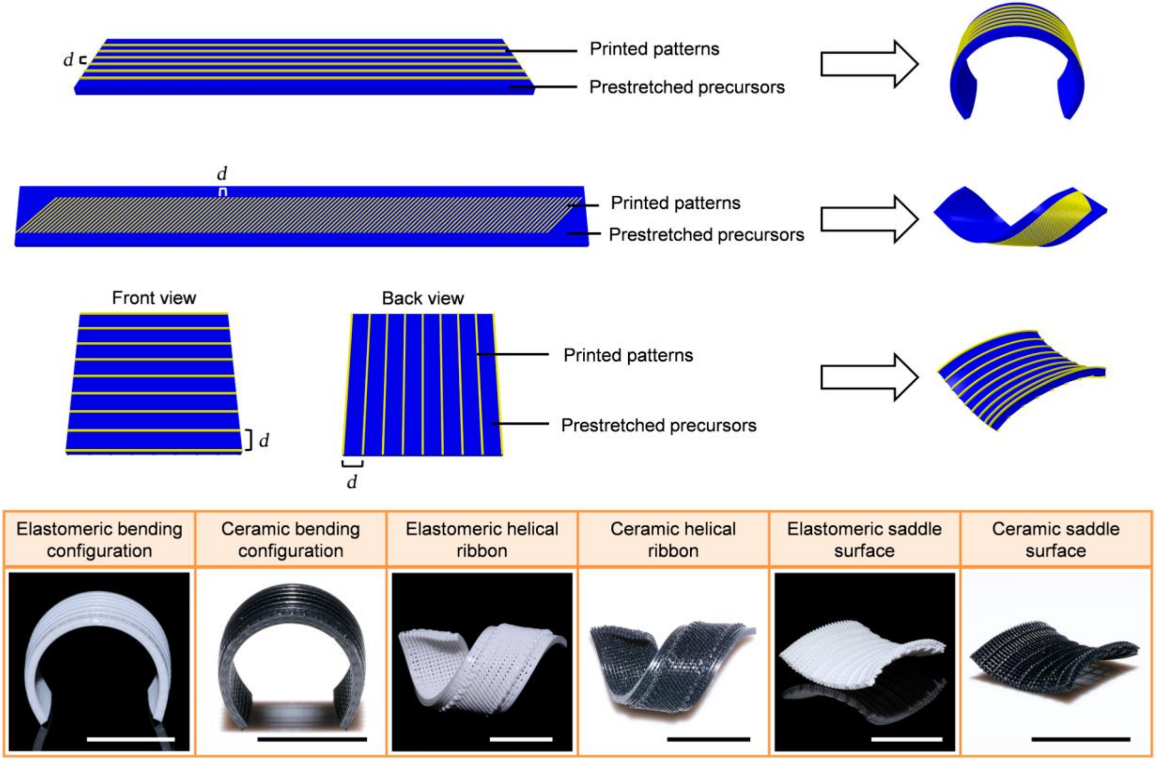

Figure 3. Four-dimensional printing of elastomer-derived ceramics (EDCs) and origami. Two typical ceramic 4D printing processes (scalebars: 1 cm). (Liu, Guo, 2018, P. [10:11])

Another breakthrough, a research team at City University of Hong Kong (CityU) has made a groundbreaking achievement by developing the world's first 4D-printed ceramics, overcoming long-standing challenges in shaping and manufacturing complex ceramic structures. Traditional ceramics are difficult to mold due to their high melting point, and conventional 3D-printed ceramic precursors are typically rigid and hard to deform. The CityU team, led by Professor Lu Jian, innovated a flexible "ceramic ink"—a mix of polymers and ceramic nanoparticles—enabling 3D-printed ceramic precursors that can stretch up to three times their original length. These elastic precursors allow intricate shaping, such as origami-like folding, before being heat-treated into durable ceramics.

The team also pioneered two 4D-printing methods, utilizing stored elastic energy in stretched precursors to achieve self-morphing structures when released. The resulting ceramics exhibit exceptional strength (e.g., 547 MPa compressive strength at 1.6 g/cm^3 density) and scalability. Potential applications include 5G electronics (due to superior electromagnetic signal transmission), aerospace propulsion systems (for high-temperature resistance), and customizable consumer products like smartphone backplates.

Published in Science Advances, this 2.5-year project marks a leap in ceramic manufacturing, combining shape-morphing versatility with mechanical robustness. Future work aims to reduce brittleness, further expanding its industrial potential. The research was supported by the Major Program of National Natural Science Foundation of China. (Net 2)

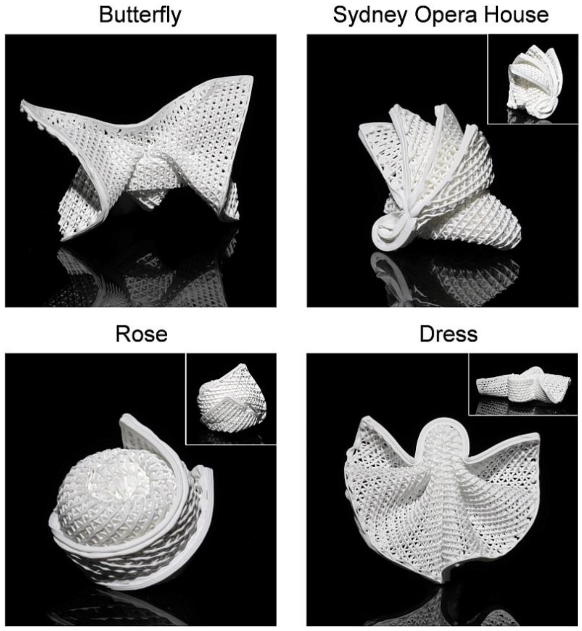

Figure 4. The 3D-printed ceramic precursors printed with the novel “ceramic ink” are soft and stretchable, enabling complex shapes, such as origami folding. (Net 2)

And this also addresses the significant challenge of 4D printing ceramics, this work introduces a viable and efficient manufacturing and design method for direct 4D ceramic printing. By developing photocurable ceramic elastomer slurry and a hydrogel precursor, hydrogel-ceramic laminates are fabricated using multimaterial digital light processing 3D printing. These flat laminates transform into complex 3D structures driven by hydrogel dehydration and subsequently become pure ceramics after sintering. A theoretical model is developed to predict the curvatures after deformation and sintering, enabling a design flow for various complex ceramic objects. This approach marks a new direction in the advancement of ceramic 4D printing technology by a method for creating curved ceramic structures. First, a laminate of hydrogel and ceramic elastomer is printed. Then, through hydrogel dehydration and subsequent sintering, this laminate is transformed into a pure curved ceramic beam. The process is also demonstrated with a flat flower laminate, where a ceramic layer is printed, followed by a hydrogel layer. This flat laminate then evolves over time into a 3D ceramic flower through a similar dehydration and sintering process. (Wang, Rong,… 2024)

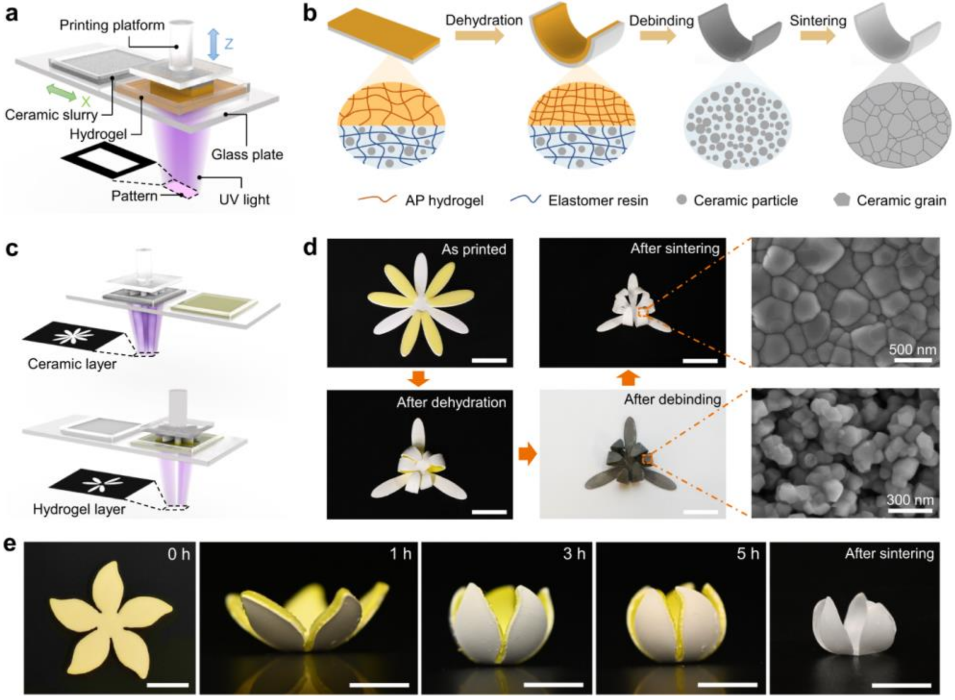

Figure 5. illustrates 4D Printing a flat layer combining hydrogel and ceramic elastomer, transforming it into a curved ceramic beam by drying the hydrogel and heating (sintering). (Wang, Rong,.. 2024)

In biomedical 3D printing excels at crafting custom medical scaffolds, but delivering complex designs into the body without major surgery remains a significant challenge. A breakthrough by creating new, smart materials called amphiphilic dynamic thermoset polyurethanes for 4D printing, specifically with an eye toward bone medical scaffolds.

These innovative materials allow us to print flat, thin scaffolds that can be folded into a simple, rod-like (1D) shape. This enables easy, minimally invasive delivery, perhaps through a small catheter, reducing the need for extensive surgical incisions. Once inside the body, the body's warmth triggers the scaffold to "pop" back into its original flat (2D) pattern. Then, as it absorbs water, different sections swell at varying rates, causing it to precisely transform into the desired final 3D structure. A remarkable feature of these materials is their ability to transition from a soft to a stiff state upon water absorption, thanks to an internal microphase separation. This water-activated stiffening is particularly crucial for providing robust support once implanted.

This unique combination of shape memory, programmable deformation, and water-activated stiffening makes our new materials exceptionally promising for creating supportive, space-filling bone scaffolds that can be implanted with minimal invasiveness, representing a significant leap forward in regenerative medicine. (Liu, Bo,… 2024)

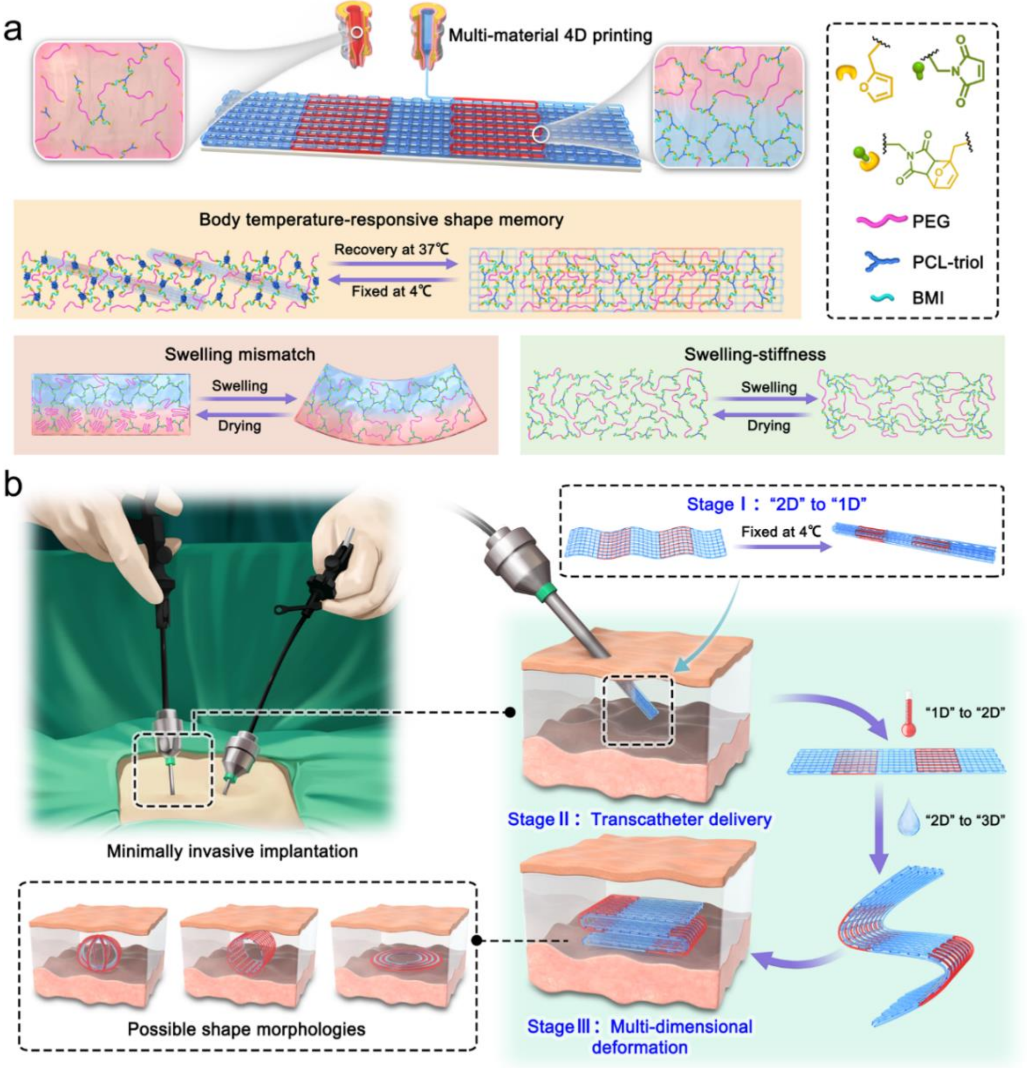

Figure 6. Programmable 4D Printed Hydrogels: Swelling, Stiffening, and Shape-Shifting for Easier Implantation (Liu, Bo,… 2024)

Research Findings:

- 4D printing technology differs from traditional 3D printing by embedding dynamic functionality directly into materials, allowing printed structures to change shape, properties, or functionality after fabrication, unlike the static objects produced by 3D printing.
- This advanced additive manufacturing technique utilises smart materials that respond to specific external stimuli such as heat, light, moisture, or magnetic fields, enabling self-transforming capabilities in the printed structures overcomes limitations found in traditional 3D printing,

particularly concerning post-production adaptability and the inherent properties of ceramics like high hardness and brittleness.
- Recent advancements in 4D printing have led to the creation of complex ceramic structures with enhanced strength and flexibility, achieved through innovations like flexible "ceramic ink" and elastomeric nanocomposites. These developments open up new possibilities for diverse applications, including biomedical devices, aerospace components, and electronics.

Research Recommendations:

As 4D ceramic printing research and material technology are still emerging in Egypt, the recommendations are:

- Focus on researching and creating cost-effective, durable, and responsive smart materials tailored to local industrial needs.
- Establish training programs for researchers dedicated to additive manufacturing with smart materials.
- Expand interdisciplinary collaboration to foster partnerships between material scientists, engineers, and clinicians for biomedical applications.
- Develop methods to reduce brittleness and improve deformability in ceramics, such as advanced sintering techniques or hybrid material composites.

Conclusion:

- This research confirms that 4D ceramic printing marks a significant transformation in additive manufacturing, fundamentally differing from traditional 3D printing by embedding dynamic functionality directly into materials. Unlike static 3D-printed objects, 4D-printed structures can change shape, properties, or functionality after fabrication. This advanced technique utilizes smart materials that respond to external stimuli like heat, light, moisture, or magnetic fields, enabling self-transforming capabilities.
- The transition to 4D ceramic printing specifically addresses and overcomes limitations of traditional 3D printing, particularly concerning post-production adaptability, like brittleness of ceramics. Recent advancements, such as elastomeric precursor and elastomeric nanocomposites, have enabled the creation of complex ceramic structures with enhanced strength and flexibility. These developments open new possibilities for diverse applications, including biomedical devices for minimally invasive implantation, aerospace components, and electronics. Ultimately, 4D ceramic printing merges the structural benefits of ceramics with dynamic functionality, expanding their potential across various industries.

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