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Ceramic Perspectives on 4D Printing Technology: A Novel Framework for Applications using Designs, Materials, Processes, and Stimuli

Shin-Hua You*, Pookkot Sivaraman Aiswarya*, David Culler** and Jia-Change Wang***

Keywords： Ceramic 4D Printing, Additive manufacturing, Smart materials.

ABSTRACT

Since the late 1980s, Three-Dimensional (3D) printing has evolved into a crucial technology for innovative product design, applications, and advanced manufacturing methods. Significant advancements have been made in printing, and researchers are continually working on controlling how materials and printed parts respond to external factors. The term "4D printing" was coined in 2013 to describe this concept. In 4D printing, models are printed with the intention of changing their shape or function in response to external stimuli, such as temperature, water, humidity, light, electric or magnetic fields. This paper reviews the current state of 4D printing, particularly in smart materials with shape memory like composites and nanocomposites of polymers, alloys, hydrogels, and ceramics. A framework identifying four key areas related to 4D printing (Design, Materials, Processes, and Stimuli) is presented. Information specific to 4D printing of ceramics was challenging to find, so the general framework and classifications for 4D printing were extended to provide more detailed information for working with ceramics and to guide future research.

INTRODUCTION

3D printing, also known as additive manufacturing (AM), has evolved over more than three decades to become a key technology in modern manufacturing. It allows for the creation of complex structures layer-by-layer, enabling the production of geometries and materials that are difficult or impossible to achieve using traditional methods. Examples include cavities, undercuts, arched channels, and overhangs. 3D printing has been successfully used in various industries, including medical, automotive, and aerospace.

Charles Hull invented stereolithography in 1983 (Bogue, 2014), marking the beginning of rapid growth in additive manufacturing technologies and materials. One of the recent advancements is 4D printing, which builds on 3D printing by allowing printed structures to change their shape or function over time in response to stimuli. This emerging field has shown remarkable capabilities and potential applications in areas such as robotics, aeronautics, and dampening systems.

4D printing relies on smart materials and metamaterials, which can be designed to exhibit specific physical characteristics and functionalities. By combining smart materials (Bogue, 2014; Zigoneanu et al, 2014; Lim, 2019) with mathematical models (Lim, 2019; Rafsanjani et al, 2015; Sydney et al, 2016), 4D printers can create static structures that transform into dynamic designs under the influence of stimuli. This innovative approach has opened up new possibilities for dynamic and adaptive structures.

Research into 4D printing has grown significantly in recent years, with a focus on exploring its potential applications, addressing challenges, and identifying new research areas. This paper aims to contribute to this field by discussing the framework for 4D printing and specifically addressing its application in ceramics.

METHODOLOGIES

4D printing builds upon 3D printing technology, which can be categorized into seven types: Material Extrusion (MEX), Vat Photopolymerization (VPP), Powder Bed Fusion (PBF), Material Jetting (MJT), Binder Jetting (BJT), Directed Energy Deposition (DED), and Sheet Lamination (SHL). Keywords for the literature search were chosen based on these technologies and shape memory materials (SMA, SMH, SMP, SMC), combined with "4D printing" using Boolean operators. The search covered

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* *Graduate Student, College of Mechanical and Electrical Engineering, National Taipei University of Technology, ROC.*
** *Professor, Department of Manufacturing & Mechanical Eng Tech, Oregon Institute of Technology, USA.*
*** *Professor, Department of Mechanical Engineering, National Taipei University of Technology, ROC.*

electronic databases like Scopus, Google Scholar, and IEEE from 2013 to 2023, focusing on emerging trends in 4D printing.

However, the search yielded a limited number of 50 documents, suggesting that 4D printing research is still relatively nascent, with less volume compared to more established fields. Most 4D printing research has utilized MEX, MJT, VPP, and PBF technologies. FDM and SLA were common techniques in MEX and VPP, respectively. Shape memory polymers (SMPs) were the most studied materials for 4D printing.

A Sankey diagram (Fig. 1) was used to visually represent the relationships between technology, material, design, and applications in 4D printing, providing insights into the field's patterns and trends.

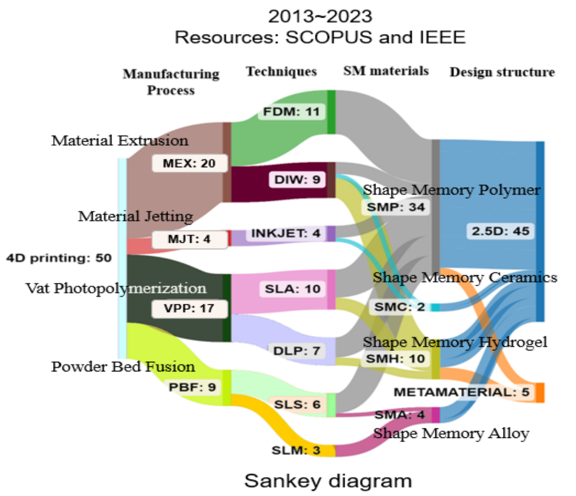

Fig. 1 Sankey diagram for 4D printing search results using 4 key elements: technology, methods, materials, and design.

CLASSIFICATION OF 4D PRINTING TECHNIQUES BASED ON DESIGN

Advancements in printing technologies and the new materials for 3D printing have made it possible to create smart materials designs that can change function or structure. By layering materials according to a preset plan in the design, 3D models can be prepared for post-construction stimuli. However, there is still a tendency to refer to all additive manufacturing technologies as 3D printing. Since it was initially described in 1984, 3D printing technology is a convergence technology that uses materials, designs, and 3D printers for specific applications. The 3D and 4D printing procedures are similar, with the product being first designed in 3D modeling software (CAD) and then fabricated with a 3D printer. The main distinctions between 4D printing and 3D printing are the use of smart designs and materials, as 4D printed structures can change in form or function. Relying on the size and connection of the framework allows for customizing it for a particular application.

2D / 2.5D Design for 4D Printing

A 2D structure is flat and has only length and width dimensions, like a sheet of paper. In contrast, a 2.5D structure adds depth to the 2D shape, creating a relief or layered structure, similar to a bas-relief sculpture. This additional dimension allows for functionalities compared to purely 2D structures. In 3D structure, it is a fully three-dimensional object, sometimes, a skeleton or metamaterial structure. 4D printing adds the element of time, where the printed object can change its shape or properties over time in response to external stimuli.

Researchers mostly use 2D / 2.5D design methods for creating structures and parts in 4D. In applications where 2D structures transform to 3D/4D using an active material, the geometry is designed using shapes that will shrink in one direction and expand in the opposite direction after being exposed to a stimulus (Goo, 2020). Exposure to these stimuli creates compressive stress that forces some parts to bend and twist (Agkathidis et al, 2022; Sydney et al, 2016; Bodaghi et al, 2019). Relaxation of the strains from the 2D structure can be exploited to build 3D structures like arcs and waves (Khang et al, 2006).

In one paper, 2D sheets are used to construct 3D and 4D forms. To fabricate a curved shape, they created a second structure for the three-dimensional shape with a base layer and a printed layer with the same elastic modulus and same elastomer. Then it is programmed to achieve its memory effect (see Fig. 2a) (Cafferty et al,2009). Another work points out the parameters of design, like the depth of the groove, the thickness of the layer, and the number of grooves, all of which can influence structural formations (Fig. 2b and 2c) (Song et al, 2021; Van et al, 2017). For applications such as actuators and sensors, developments of 4D printing design structure primarily influences 2D/2.5D structures because of its efficiency in flexible mechanisms. Further research was done to improve the mechanical functionalities, leading to potential behavior as a Metamaterial.

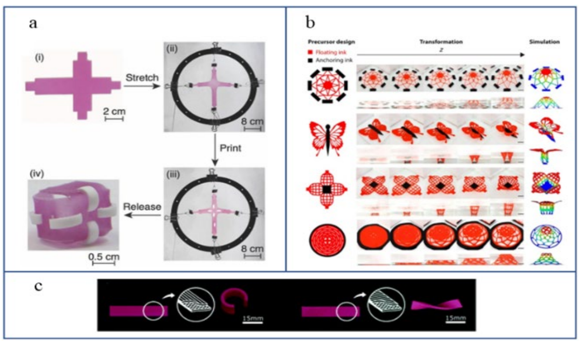

Fig. 2 2D Design structures used in 4D applications: 2a shows fabrication process of elastomeric quasi cube (Rogers et al, 2019), 2b 2D structures with simulations (Song et al, 2021), 2c combination of infill resulting in shape shifting (Van et al, 2017).

3D Metamaterial Design for 4D Printing

Metamaterials, as described by Victor Veselago in 1967, are engineered to possess unique properties not found in natural materials due to their unique microstructures (Veselago, 1967). These materials can exist in 2D or 3D forms, featuring curved structures and patterns that exhibit distinctive electromagnetic characteristics and capabilities achievable through 3D printing (Sadeqi et al, 2019; Bodaghi et al, 2017). Metamaterials consist of arrays of individually constructed unit cells that perform functions not inherent to the material, often requiring high resolutions to create intricate details (Jiang et al, 2016; Li et al, 2009).

Recent advancements have enabled the tailoring of macroscopic physical properties, including mechanical, acoustic, thermal, and electromagnetic, by adjusting topological characteristics and microstructure arrangement. However, many additive manufacturing (AM) technologies face challenges in printing metamaterial structures due to segment thickness ranging between 200 and 50 µm, with some features only functional at the nanometer scale.

Improvements in printer techniques, such as optimizing 3D printing parameters, have aided in achieving desired meta-structures. For instance, in one study, a filigree actuator (minimum strut diameter: 500 µm) was designed for a one-way shape memory system. The metamaterial design structure enabled mechanical and functional properties such as flexibility, extensibility, high stiffness, stability, and a negative Poisson's ratio, while also being lightweight. These outcomes were attained by optimizing the connectivity and geometry (angles, size, and thickness of each unit segment) of the structures, resulting in an actuator with the desired stiffness and greater forces.

As depicted in Fig. 3a, Kim et al design the geometries of the metamaterial structures fabricated via the L-PBF of the Fe-SMA, the results show that the applied tensile load can be effectively converted into shear deformation through different designed metamaterial structures (Kim et al, 2022). To verify the shape memory behaviour, Li et al tested the self-adaptive unfolding performance of one snowflake-like unit cell as show in Fig. 3b, by heating the heating platform and giving it different temperatures, the changes in the shape memory period of the printed snowflake-shaped unit cells can be observed (Li et al, 2021).

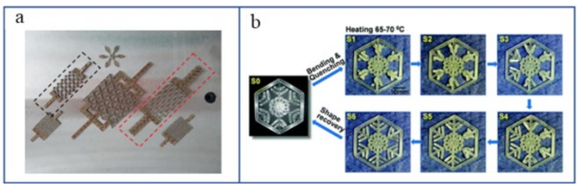

Fig. 3 Metamaterial design structures applied in 4D applications: (a) Metamaterial structures fabricated using SMA BY PBF technology (Kim et al, 2022), (b) metamaterial structure showing its shape memory cycle (Li et al, 2021).

Sensors, absorbers, acoustic cloaks, and antennas are among the most common uses for metamaterials. Because AM can produce complicated structures (and resolutions) that are impossible to achieve using traditional manufacturing methods, creating complex metamaterials is now possible (Jiang et al, 2016; Li et al, 2021). The combination of 4D printing and metamaterial structures will expand the field of design applications to allow self-adaptability, self-sensing, shape memory, decision-making, and multiple functions (Boley et al, 2019; Kamila, 2013). These attributes affect how printed components change their properties in response to external stimuli, and they open a wide range of potential applications for these materials. Recent advances in 4D printing that use a single, smart material, stimuli, or a mixture of materials as the starting form, have improved tuning adjustments to the mechanical metamaterials' structure and functionality under the effects of different stimuli.

4D Printing Techniques in Ceramics Based on Design

Most industrial ceramic components or structures are currently simple in design. However, ceramics' potential for high precision and low surface roughness makes them suitable for creating complex metamaterial structures for 4D applications. Hierarchical design principles could transform ceramics from strong, dense, and brittle materials into strong, ultralight, energy-absorbing recoverable metamaterials (Meza et al, 2014; Wroblewska, 2001).

Designing at the nanoscale involves structures like quadrangular pyramids, octet trusses, honeycombs, and auxetic structures. Adapting these designs to ceramics has shown significant recovery deformations (up to 95%-98% after compression to 50% strain) and controlled thermal expansions, particularly in piezoelectric ceramics, enhancing their mechanical and piezoelectrical properties for applications such as energy harvesting (Meza et al, 2014; Wroblewska et al, 2001; Zhang et al, 2021; Köllner et al, 2023; Liu et al, 2021).

These studies demonstrate the potential of metamaterial design to enable novel technologies and applications previously unattainable with traditional ceramics. 4D printing of ceramics is still in its early stages, with much research focusing on material properties. One challenge in 3D printing ceramics is shrinkage during sintering, which distorts objects; however, this limitation can be advantageous in 4D applications. Combining hierarchical design principles could achieve shape morphologies like twisting and folding. Additionally, ceramic metamaterials could be engineered to have a negative thermal expansion coefficient, contracting instead of expanding when heated. This property is crucial in aeronautical applications to prevent damage from temperature variations.

CLASSIFICATION OF 4D PRINTING TECHNIQUES BASED ON MATERIALS

The smartness of the materials is more significant in achieving the expected reaction in printed components that consist of a single, smart material or a mixture of smart and conventional materials than in multi-material segments. The smartness of smart materials or combinations refers to the materials' / mixtures' self-adaptability, self-sensing, shape memory, decision-making, and multi-functionality (Veselago, 1967; Sadeqi et al, 2019). These attributes affect how printed components change their properties in response to external stimuli and open the potential for a wide range of applications for these materials. Recent advances in 4D printing that use shape memory effect materials can be categorized as SMAs, SMPs, SMHs, and SMCs, each of which will be highlighted in the following sections.

SMA

Shape Memory Alloys (SMAs) are composed of alloys from various metals that can undergo significant reversible deformations under thermal stimuli, generating increased temperature and mechanical driving forces. SMAs conduct reversible changes in lattice structure in models printed with 3D/4D printers through thermal and mechanical stress. They can be used alone or as a matrix for complex composite structures, often referred to as intelligent materials and smart composites (Meier et al, 2009; Huebsch et al, 2012).

The Shape Memory Effect (SME) of SMAs involves converting thermal energy into mechanical work (Fremond et al, 1996; Fremond et al, 1996). This effect occurs due to the transformation between two crystalline phases in SMAs: the low-temperature martensite phase and the high-temperature austenite phase. Reversible phase transformation can be achieved when an SMA is deformed in the martensitic phase and then heated above a certain temperature (Fremond et al, 1996; Fremond et al, 1996; Thrasher, 1992; Leo, 2007). This process allows the alloy to recover its original shape as the crystalline structure shifts from martensite to austenite. SMAs also exhibit superelasticity, which is the ability to recover a significant amount of strain when loaded and unloaded. Unlike SME, where temperature changes trigger reversible martensitic phase transformation, superelasticity's phase transformation is driven by mechanical activities (Fremond et al, 1996; Fremond et al, 1996). Nickel-titanium SMA is an example, demonstrating both SME (thermal memory) and superelasticity (mechanical memory). Fig. 4 presents several post-cured structures manufactured by 3D printing from Ni-Mn-Ga powders.

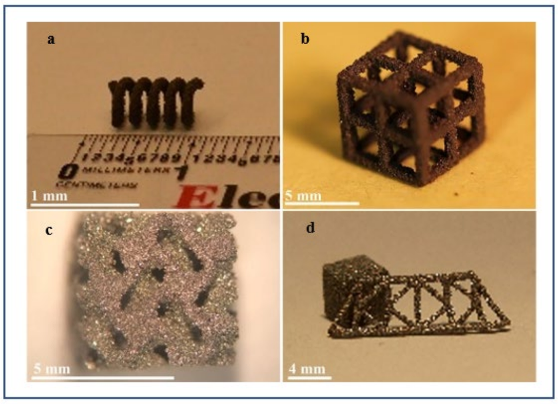

Fig. 4. The SME in SMAs (Ni-Mn-Ga): (a,b,c,d) Magnetic shape memory effect Ni-Mn-Ga powder printed structure (Caputo et al, 2018).

SMP

SMPs are polymers that" recall and memorize" their initial shape and can revert to it after deformation if an external stimulus is applied—usually a higher thermal stimulus. According to one study, the possibility of employing PLA's shape memory capability to restore the original shape while being heated up to 98% at 65 °C (Qu et al, 2023). Fig. 5a shows the feasibility study of 4D printing IVCFs in vitro of shape memory inferior vena cava filter (IVCF), By heating the model to 40 degrees Celsius to shrink it, the model can be inserted into the blood vessels. Then, at a temperature close to the human body temperature of 37.8 degrees Celsius, the model regains its shape, thereby achieving the medical purpose. One study synthesized a new material suitable for 4D printing, as shown in the Fig. 5b, a flat structure model, such as a square box, was printed and then deformed into a box shape under external force at 67°C, the model's shape can be reconfigured by fixing the box with a hard aluminum foil package and heating it to 120°C for 1 hour, this method helps in its repeated use.

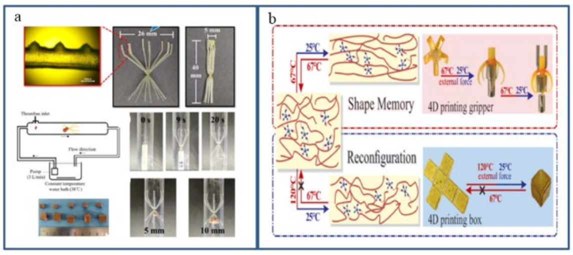

Fig. 5 Shape Memory Effect of Polymers: (a) pictorial representation of the process of 4D printed IVCF (Implantation of Inferior Vena Cava Filters) (Qu et al, 2023), and (b) shape memory recover process of 4D printed IEMSi applied as a gripper and intelligent packaging box (Miao et al, 2019).

The basis of two mechanisms underlying polymers is known as net points and switching segments, in which the switching segments are essentially crystallites. Net points are primarily based on chemical and physical crosslinks. The SMPs are categorized as physically and chemically crosslinked, the lighter weight, more reliable recovery performance, milder recovery conditions, biodegradability, low biotoxicity, and no toxicity characteristics of SMPs make them stand out over other smart materials. Shape-memory applications employ polymers with bases like polyurethane, Polylactic acid (PLA), and epoxy because of their ease of processing and the fact that they are inexpensive. PLA, the most well-known SMP, is a commonly used material in FDM 3D printing. However, many more SMPs can be 3D printed to combine the capabilities of creating new, complicated structures that can restore their shapes after unintended or intentional distortion (Jiang et al, 2016).

Researchers have been testing SMPs for 4D printing applications in recent years. According to one author, dynamic halogenated bisphenol carbamate bonds were used to generate a self-healing, recyclable polyurethane with high mechanical strength and excellent flexibility (Sun et al, 2020). Suong Hoa et al. used SMPs with 4D printing to make a shape-changing wing structure created for use in unmanned aerial vehicles (UAVs). The researchers used a combination of 3D printing and shape programming techniques to develop SMP structures that could change shape in response to heat. They found that 4D printing with SMPs allowed for creating highly efficient and lightweight UAV wings with shape-changing capabilities. 4D printing with SMPs has potential applications in fields such as aerospace, medicine, and materials science, and further research in this area is likely to lead exciting new developments (Hoa et al, 2022).

SMH

A hydrogel is a solid jelly-like substance with qualities ranging from soft and pliable to rugged and durable. A polymer hydrogel is a 3D crosslinked network of flexible polymer chains containing a lot of water and yet having solid attributes (Zhu et al, 2019). The 3D network allows liquid retention to form a swelling gel section, and the liquid inside can prevent the polymer network from collapsing, giving it lax skin-like properties. A polymer sol or solution can quickly transition from a structure with high viscosity in the liquid state to a solid phase hydrogel at the gel point (sol-gel transition) (Patel et al, 2015).

In SMHs, temporary shapes are fixed, and the original shapes can be restored by forming or destroying reversible crosslinks (for instance, elongation, compression, or folding) in response to external stimuli (for instance, heat, magnetism, light, and chemicals). As a result of this approach, some SMH networks maintain their fixed forms while dynamic networks are employed for memory-related functions. The thermo-responsive SME was initially studied in a crosslinked poly (acrylic acid) based network with a primary hydrophilic chain (for swelling caused by water ingestion) and short dangling stearyl side chains. Whenever the temperature rises beyond 50°C, the gel becomes extremely soft and may be stretched at least 1.5 times its initial length (Osada et al, 1995).

Another example demonstrates a hydrogel actuator with temperature control that can change form in reaction to swelling in the water created using SMHs in a bilayer framework. The bilayer displays swelling-induced 'line-to-coil' bending, and the evolution of the bilayer's curvature over time under variable temperature settings, thereby clearly demonstrating the phenomena of directed bending (shown in Fig. 6a) (Wu et al, 2021).

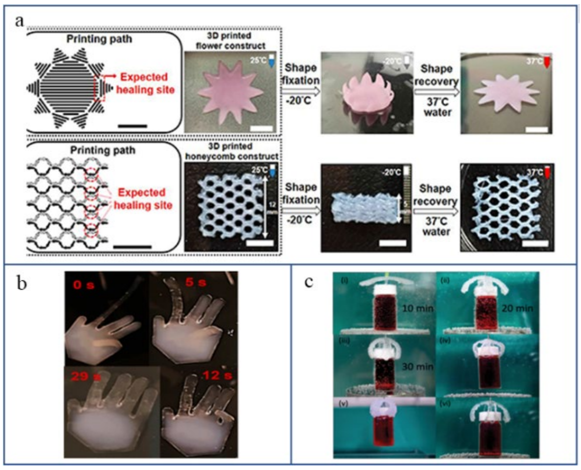

Fig. 6 SME in Shape Memory Hydrogels: (a) Shape memory and self healing of PUGG hydrogel with UV and temperature simulations (Wu et al, 2021), (b) Shape recovery process of 4D printed robotic hydrogel hand (Abdullah et al, 2023), (c) shape memory application of 4D printed gripper SMH (Shiblee et al, 2019).

Another work cited shows the shape memory and recovery process of hydrogel within the application of a printed robotic hand. Hydrogels that are submerged in water cause physical crosslinking through contacts in between hexadecyl side chains of the C16A molecule. This presence of the C16A crystalline domains causes the hydrogels to display a bidirectional strong-to-weak gel transition between 36 and 41°C. Once the fingers were folded and stretched, they were cooled to 20 °C to provide a temporary form for the hand. The hand was then submerged in 43 °C water to achieve the form recovery. The outcome demonstrates that folding and stretching result in form recovery, and the printed hand may completely regain its original shape in less than a minute Fig. 6b

(Abdullah et al, 2023).

The stimuli that cause hydrogels to change into different shapes include electromagnetic, pH, light, ions, temperature, and salt concentration. After being exposed to UV light for one minute, the printed hydrogel exhibited remarkable morphological and mechanical properties. Several deformation cycles and shape memory programming were applied to the printed hydrogel. The 4D printed constructions with shape memory demonstrated high form persistence (95 %) and shape recovery at 37 °C (98 %) (Fig. 6c) (Shiblee et al, 2019). 4D printing with smart hydrogels has potential applications in fields such as soft robotics, biomimetics, and wound healing. New applications are currently being developed.

SMC

Ceramics contain unique properties that give them advantages over any other memory material that give ceramic-based shape memory infinite potential. Compared to form memory metals, ceramics' extremely high strength enables access to super elasticity and shape memory at high-stress levels. Compared to shape memory metals, ceramic is more rigid, accesses greater stresses, and has a greater chance to increase the hysteresis area. As a result, it can reversibly dampen significant mechanical energy. Lead zirconate titanate ferroelectric and partly stabilized zirconia are two examples of ceramic materials that exhibit memory capabilities. SMCs have four ways of recovering their original shapes viscoelastic, martensitic, ferroelectric, and ferromagnetic. Each of these mechanisms exhibits shape memory behavior through a different set of procedures (Lai et al, 2013).

Guo Liu et al. have developed a new method of 4D printing with ceramics that allows for the creation of complex, shape-changing structures. In this work, they set Ceramic with a combination of 3D printing and ceramic powder sintering techniques to create ceramic structures that can change shape in response to temperature changes. These shape-changing ceramics also created tunable microwave components for use in communication systems and computing devices, which also opened potential for creating an adaptive thermal management system for aerospace applications, helping regulate the temperature of spacecraft and satellites (Liu et al, 2018).

4D printing with ceramics is still a relatively new field, and it will revolutionize materials science and engineering. The ability to create ceramics with tailored mechanical properties and shape-changing behavior could lead to breakthroughs in aerospace, energy, and medicine. On the other hand, the printing process for ceramics is more complicated than with other materials, making intricate structures more challenging to manufacture. Controlling the shape-changing behavior of ceramics, which may be influenced by various elements such as temperature, moisture, and stress, is also tricky. Other disadvantages are that ceramic materials are often more expensive than other materials used in 3D printing, and they use more energy for heat during sintering, raising the cost of using the technology.

4D Printing Techniques in Ceramics Based on Materials

The ceramic material attributes of lightweight, high dimensional stability, weather resistance, elastic modulus, melting point, exceptional chemical inertness, high thermal conductivity, and resistance to corrosion render them very desirable for industrial utilization. However, to integrate these attributes into both 4D and 3D applications, it is necessary to transcend the constraints of ceramics, specifically their elevated melting point, through combining them with polymers (Meza et al, 2014; Bargardi et al, 2016; Romanczuk-Ruszuk et al, 2023).

The augmentation of elastic properties has paved the way for the emergence of 4D applications that exhibit the ability to undergo reshaping and reassembly. The utilization of piezoelectric materials, as well as the incorporation of precursors such as Polydimethylsiloxane (PDMS), have been shown to effectively mitigate the sintering temperature requirement while simultaneously augmenting the shape memory effect in ceramics (Meza et al, 2014; Bargardi et al, 2016).

Other unique material properties of ceramics challenge researchers in 4D printing like brittleness, high melting point, limited deformability, and porosity. 4D printing composite ceramics with elastic properties may help with forming and brittleness. Altering the chemical composition of the ceramics materials by adding dopants such as rare earth ions or other additives can enhance the luminescence property in ceramics. 4D printing porous ceramics can be applied in acoustic and filtration with tailored porosity by controlling pore size distribution and connectivity, giving them self-healing potential. Porous or nanocrystalline ceramics can also have faster responses times to changes in humidity.

4D PRINTING TECHNIQUES

The 4D printing techniques listed in Table. 1 are steps forward from 3D printing. This section will review the various printing techniques used in 4D printing and identify current trends. There are seven main categories for 3D printing technology listed: material extrusion, material jetting, vat photopolymerization, direct energy deposition, sheet lamination, binder jetting, and powder bed fusion. Up to now, only a handful have been employed for 4D printing due to cost effectiveness, material availability, improvement in the structure, and applications that demand specific properties. Based on the varied approaches to smart materials, design structure, and desired functionality, we must choose the most appropriate 3D printing technique for fabrication.

Table. 1 Table enlist the advantages and limitations of techniques in 4d manufacturing process.

Manufacturing processes	**4D Printing Advantages**	**Limitations**
Material Extrusion	Affordability, control of printing temperature and printing speed, optimum layer thickness	Average accuracy, speed rate, and resolution structures.
Material Jetting	Economic, non-contact method of deposition compatibility with different materials, high resolution, high speed of printing, and less post-processing.	Meager speed, need for compatible materials and optimized inkjet printing parameters, contamination.
Vat Photopolymerization	High-resolution output, power-controlled light source, Versatile in light intensities, scanning speed, exposure time, and flexible construction.	Relatively expensive, lengthy post-process
Powder Bed Fusion	No support needed, friendly in printing metal ceramics, High dimensional accuracy without the need for a vacuum environment	High power consumption and rough surface finish which led to long post-process

Material Extrusion

4D printing based on Material Extrusion (MEX) is the most widely utilized technology for quick prototyping and manufacturing customized plastic parts straight from CAD models (Choi et al, 2015).

Fusion Deposition Modelling (FDM): FDM is a printing technique in which the material to be printed is extruded through a nozzle and hardened on a substrate. A motor supports the nozzle, moving it in the X and Y axes. When a 2D layer is printed on a substrate, the nozzle is pushed upward in the Z-axis, and a new layer is printed on top of the old. This approach uses a layer-by-layer addition until a finished 3D or 4D printed structure is achieved. FDM is one of the most often used 3D printing methods for 4D printing. Certain printing parameters could enable the 4D complex structures to attain their functional property, as in case the embedding of inhomogeneous built-in strains into precursory patterns which produce localized bending during heating was achieved by spatially adjusting the printing speed. Also, the addition of a built-in strain and enabling a more comprehensive range of curvature variation by lowering the temperature of the print nozzle/build platform.

A nozzle with a temperature-controlled heating element that could print thermoplastic elastomers with varying degrees of stiffness could provide versatile structure functionality during the stimulus, which could be applied in 4D printing applications. The printing parameters effectively impact the material and design structure, which also influence the functionalities. One of the works emphasizes the utility of 3D printing parameters and their influence on the degree of shape-shifting, showing how raising print speed leads to an increase and lowering nozzle temperature and layer height results in a decrease. While the printing settings impact the size of the strains, the printing pattern impacts the direction of the stains, which results in shape-shifting behaviors in Fig. 7 (a and b) (Nezhad et al, 2022).

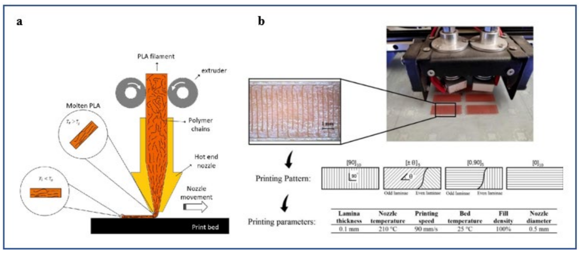

Fig. 7 Pictorial representation of Material extrusion process:(A) Schematic illustration of the constrained thermal and mechanical mechanisms in 4D printing of FDM, (B) printing patterns and conditions used to print samples with an FDM 3D printer. (Nezhad et al, 2022).

Direct Ink Writing (DIW): DIW is a widely used technique for 4D printing due to its ability to print complex geometries and the potential for multiple materials to be printed in a single process. The most commonly used materials for DIW 4D printing are hydrogels and elastomers because they can undergo large deformations in response to stimuli. Most of the 4D medical applications need to be constructed accurately, like in the case of drug delivery, since it's delivered into a living being. Printing resolution can range from hundreds of nanometers to hundreds of microns. High printing resolution is made possible by using micronozzles in DIW, which is advantageous when considering radio frequency and independently powered microdevices. Hongqiu Wei et al. developed a DIW that enables layer thickness even to 0.1 micrometers which could help in printing nanomaterials in a desired complex structure which in turn eases the desired functionality in the 4D applications. The cross-linking between poly (lactic acid) chains was enhanced when exposed to UV light, which improved the shape memory behavior of the printed structure Fig. 8a (Wei et al, 2017). DIW is also easily customizable depending on the desired functional materials. UV-aided DIW was used to print a highly stretchable shape memory and self-healing elastomer for biomedical repair devices and wound-healing applications Fig. 8b (Kuang et al, 2018).

DIW is a promising technique for 4D printing due to its ability to print complex geometries and multiple materials in a single process. Fig. 8c (Chen et al, 2019) shows a Schematic printing process of graded multi-material assisted by dynamic photomask by Kaijuan Chen et al. developed a novel approach to the fabrication of multilevel triboelectric nanogenerators (TENGs) using a combination of Direct Ink Writing (DIW) and Dynamic Photomask-Assisted Direct Ink Writing (DPADW) techniques. The use of the DIW method in this context had several significant effects on the performance of the TENG, where it allowed for the precise control of the layer thickness and composition, which is critical for optimizing the TENG's performance. Furthermore, it enabled the creation of complex, multi-material structures that would be difficult or impossible to fabricate using traditional manufacturing techniques. Its potential applications include soft robotics, biomedical engineering, and intelligent materials. However, further research is needed to optimize the printing process and materials used to reach the potential of 4D printing using DIW.

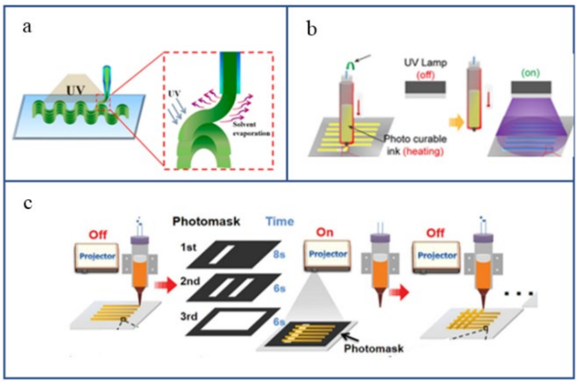

Fig. 8 Schematic diagrams of DIW process: (a) Schematic diagram of constructing 3D structures using PLA-based inks layer-by-layer under UV irradiation (Wei et al, 2017), (b) Schematic diagram of 4D printing tough and isotropic epoxy with an aided UV light and post-process (Kuang et al, 2018) and (c) Schematic printing process of graded multi-material DIW aided with dynamic photomask (Chen et al, 2019).

Material jetting

Inkjet: Inkjet printing is another popular printing process due to its ability to print a wide range of materials with high resolution. Single and multiple nozzles can function simultaneously, and different light-curable liquid resins can be sprayed on the printing platform to build a layer that is then used for light-curing. Components of other materials can be fabricated this way at a high resolution. For multi-material printing, however, the usual planar resolution of an inkjet printer reduces rapidly from 30µm – 40µm to 200µm – 400µm compared to single nozzle printing. Inkjet printers can print insoluble materials such as metals, metal oxides, and ceramics deposited as nanoparticles. The printing of some functional organic materials and living cells is possible. One of the studies by Chunxiao Cui (Cui et al, 2020), uses inkjet printing to create a microscale structure that can self-fold into a specific shape when exposed to heat.

Using this idea, a 4D inkjet printer was developed which could not only micropattern the self-fold into a 3D scaffold at the same time but also seeds live cells onto the micropatterns before self-folding which produces cell-encapsulating 3D scaffolds, with layer-wise cell-cell organization, where a double-scan strategy significantly improves the uniformity and repeatability of single droplets, ensuring the printing of 2D micropatterns with consistent droplet sizes. Another advantage of using the inkjet technique is that the materials are solutions or suspensions of particles and can be deposited and patterned by ejecting micrometric droplets rapidly from nozzles, each controlled meticulously and individually. Inkjet printing is a relatively quick and inexpensive process that works with various materials.

Vat Photopolymerization

Vat Photopolymerization is a fast and precise 3D printing technology that produces uniformly high-quality finished objects. In the realm of engineering, stereolithography is commonly employed (Weems et al, 2019). In this scenario, the object is made by photopolymerizing a liquid resin into a solid. In a resin vat, a laser is directed to a specified depth, inducing localized polymerization (and solidification). Solidification is repeated layer by layer until a solid, three-dimensional item is created (Kodama, 1981). The amount of polymer and photo initiator used in printing is controlled by the power of the light source, scanning speed, exposure time, and the amount of polymer and photo initiator used (Zhao et al, 2021). The main benefit of stereolithography printing is its adaptability and construction. Such structures can be placed in the damaged area and self-assembled to eliminate the flaw. In addition, if bending or jointing is necessary for a specific building area, a 4D printed material can be used that has been proven to flex and bend.

Another printing process utilized in 4D printing technology is SLA (Stereolithography). A light-sensitive substance (photopolymer) is employed in this process that solidifies when exposed to light. Various radiations, such as UV, visible, X-rays, electron beams, and so on, can be utilized to harden the substance. However, only UV and visible lights are used commercially. The principle is simple: light strikes the substance, causing a curing reaction in which the resin molecules bond to form a solid structure. The viscosity of the photopolymer increases as it cures, transforming into a gel, which then transforms into a solid crosslinked polymer. SLA has been used to fabricate complicated and structurally demanding structures with great success.

Compared to traditional SLA technology, DLP technology cures the complete pattern in a layer with one single exposure, thus increasing efficiency. Zhao et al. employed DLP to print polyethylene glycol diacrylate (PEGDA)- based environment responsive self-folding origami structures (Zhao et al, 2021). The different light intensities create thin polymers with varying degrees of crosslinking. Ge et al. used Projection Micro Stereolithography (PSL) to create multi-layer shape memory objects made of different methacrylate copolymers using a high-resolution DLP (Gauvin et al, 2012). Advances in micro-stereolithography with resolutions as high as 40 nm (Lim, 2019) have recently been made. Invernizzi et al. used DLP to print objects using the PCL/ ureido-pyrimidinone (UPy)-based polymer. These materials showed good shape memory and self-healing capabilities, making them suitable for use as soft actuators (Invernizzi et al, 2018). Liu et al. printed a self-folding box and a stimuli-response gripper using a new shape-memory polyimide ink with excellent mechanical strength and low contraction (Liu et al, 2022). Devillard et al. created a biomimetic construct of vascularized alveolar bone using DLP-based 3D printing technology (Devillard et al, 2018). Ang Li et al. made a High-performance, lightweight architecture with high strength, high recovery stress, perfect shape recovery, and good recyclability with DLP. DLP 3D printing with the 3D-RSMP resin achieved high-quality and high-resolution cubic micro lattice with.015mm layer thickness with vertical printing (Li et al, 2019).

Powder Bed Fusion

Powder Bed Fusion (PBF) is a common 3D printing technique that uses a high-powered laser or electron beam to melt and fuse layers of powdered material. Researchers have been exploring using PBF for 4D printing applications in recent years. One of the main advantages of the PBF technique is that no supporting structures are needed for 3D printing when fabricating hollow structures due to the solid powders' properties. In addition, compared to other techniques, the 3D printed part using PBF has higher strength and better mechanical properties. These advantages open new possibilities in the manufacturing of 4D functional structures. Several studies have focused on using PBF for the 4D printing of shape memory alloys (SMAs). SMAs are materials that can change shape when heated or cooled. A study that used PBF to print a model using Fe-SMA for shape morphing complex structures that could change shape in response to heat was successful. The researchers found that PBF effectively created SMA structures with precise geometry and good mechanical properties (Kim et al, 2022). The laser helps in melting the polymer powders and assembling layer by layer to build a 3D structure (Ligon et al, 2017), demonstrating the value of 4D printing conductive materials and polymer composites. Hongzhi et al. (Wu et al, 2020) fabricated a magnetic polymer composite using Selective Laser Sintering (SLS)-based 4D printing of magnetism composites with high mechanical strength and made a magnetism-driven 4D SLS printed object where the magnetic particles were uniformly distributed due to thorough and fast mixing Fig. 11. In another case, 4D printing of PUDA materials with dynamic crosslinking exhibited characteristics of an isotropic mechanical property because of its good interaction within the interlayer. To achieve large and controllable energy density, the scanning speed and spacing of the laser were set to a minimum (Ouyang et al, 2022). Regarding compression strength and accuracy, illustrations printed with quarry debris perform similarly to those printed with silica sand (Bhavar et al, 2017).

These studies suggest that PBF is a promising option for the 4D printing of various materials, including SMAs, SMPs, and composites. In addition, PBF allows for the creation of complex and precise structures with good mechanical properties and demonstrates potential for applications in fields such as medicine, aerospace, and robotics.

4D Printing Techniques in Ceramics Based on Technology

When employing the 3D printing process for ceramics, it is important to carefully consider various key factors related to its production. One is that the realization of undeformed objects that exhibit well-defined geometries can be a challenge and the other is that achieving optimal levels of strength and density require consideration during both the design and fabrication of these objects. The material extrusion and vat photopolymerization processes are the dominant technologies utilized for ceramic 3D printing.

The process of Material Extrusion is predominantly employed in the domain of ceramic 3D printing due to its inherent efficacy in rendering products with high quality physical and mechanical properties. Moreover, this technology is relatively cost-effective when compared to other 3D printing modalities, thereby allowing the printing of a wider range of pore sizes and facilitating optimal material utilization (Meza et al, 2014; Bargardi et al, 2016; Romanczuk-Ruszuk et al, 2023; Liu et al, 2018; Wu et al, 2017).

Vat photopolymerization (VPP)-based ceramic printing is highly valued for its ability to achieve high resolution, rapid printing speeds, improved grain isotropy, and enhanced surface quality of printed products through the utilization of microscale/nanoscale ceramic particles (Liu et al, 2018; Li et al, 2021).

4D printing technology for ceramics is still in the early stages of development and investigation. Printing with high resolution and printing speed has been achieved but still problems like material waste and clogging of print nozzles have yet to be solved. Controlling the viscosity of the material flow on the nozzle with heat elements could be a solution for the clogging issues. Extrusion technology saves materials compared with stereolithography technology but the detailed finishing for complex structures is accomplished mostly by stereolithography technologies. Introducing scrapper blade technology in stereolithography by controlling the scrapper blade speed, and angle could help in reliably fabricating tailored 4D printed ceramics.

4D PRINTING CLASSIFICATION BASED ON THE STIMULI SOURCES

Aside from smart materials, unique geometries, and 3D printing techniques, transitioning from 3D printing to 4D is accomplished by using an external stimulus. The programmed 3D-printed smart structure turns into the desired structural and functional attributes as a reaction. Stimuli have been classified as being either internal or external. Most smart materials are sensitive to external stimulations. The most common external stimuli applied up to now are moisture, heat, electricity, and magnetic fields. Conversely, the cell traction force is the most common internal stimulus (Dai et al, 2013). Table. 2 summarizes the principles, benefits, and drawbacks of some of stimuli used in practice.

Table. 2 Shows the 4d printing stimulation method (Dai et al, 2013)

Simulation Method	Theory	Advantages	Disadvantages
Water / humidity	Swelling / Shrinkage	Clean / Convenient	Slow response
Temperature	Internal stress inequality	Controlled adjustable	Slow response, complicated
Light	Photo-thermal effect	High-resolution control/remote control	Complicated
Electric field	Electro-thermal effect	Fast	Operating inconvenience
Magnetic field	Magnetic drive	Remote control	Operating inconvenience

Stimuli for Water and Humidity

4D printing introduced the idea of water and humidity as stimuli. Because of their demonstrated reactions and broad applicability, materials sensitive to water or humidity are of tremendous interest. After drying, a designed component can be deformed underwater and then returned to its original shape by employing water as an external stimulation. To ensure the integrity of the printed structure, the humidity-sensitive material's degree of expansion/contraction should be adequately managed during the transition (Dai et al, 2013).

Temperature Stimuli

Temperature Stimuli in polymer-based materials is one of the most often employed shape-shifting stimuli. It has been able to print an SMP flower that bloomed when heated. Smart grippers with no assembly or electromechanical components are also made with this technology. Some of the latest research reveals that SMP structures can be pre-programmed by utilizing the heating process in FDM printers. A graphene-based piezoelectric structure that expands into a plate when heated and cools back into a cylinder was employed. SMP with glass transition was used to build a phenomenological model that introduced the idea of phase evolution. The SMP sample deforms from its original shape at a temperature greater than its transition temperature in a typical shape memory cycle. It then cools to a lower temperature while keeping external constraints in place. For example, fiber-based glass polymers exhibit a shape memory effect (SME) (Tg) when heated above their glass transition temperature (Dai et al, 2013).

Light Stimuli

Light is a popular stimulus for distant induction, which governs the polymer shape. A light trigger with varying wavelengths can change the form of the polymer. This stimulus can be employed in biomedicine and medication delivery in living organisms because it does not harm the cells by raising the substance's temperature (Dai et al, 2013).

Stimuli in the Electric Field

An electric field, like light, can be employed as a stimulus using remote control. When utilized as a stimulus, the electric field provides a resistive mechanism to fill an SMP with a conductive filler. The photo series depicts the sample's electromagnetic induction shape memory effect. Resistance generates heat when an electric field is applied, forcing the mechanism to respond (Li et al, 2014; Yakacki et al, 2005; Bodaghi et al, 2018).

Stimuli in the Magnetic Field

To accomplish magnetically induced shape recovery, SMP can be doped with magnetic nanoparticles (such as Fe_2O_3 and Fe_3O_4) (Li et al, 2014). Breger et al. incorporated magnetic nanoparticles into a hydrogel-printed micro-clamp and used a magnetic field to achieve remote control (Wazeer et al, 2023). Magnetically induced thermoplastic SMP composites loaded with Fe_2O_3 nanoparticles were investigated by Mohr et al (Weigel et al, 2009). Heating in an alternating magnetic field can cause form recovery in SMP composites.

4D Printing Methods Used in Ceramics Based on

Stimulus.

Another important aspect of 4D printing pertains to the implementation of external stimuli that activate functional properties. Ceramic objects produced with 4D printing technology possess the ability to alter their shape and morphology in response to external stimuli, including magnetic fields, temperature, and electrical or mechanical force.

The initial 4D printing of ceramics, which utilized precursors, involved the deployment of built-in energy that is then released during the heat treatment stage, resulting in effects on ceramics (Meza et al, 2014; Zhang et al, 2021; Romanczuk-Ruszuk et al, 2023; Liu et al, 2018). Ceramic materials can exhibit a variety of different behaviors under different stimuli depending on their composition and microstructure. The most used stimuli are thermal, electrical, and magnetic.

Thermal stimuli: The process of 4D printing ceramics under thermal stimulus typically involves the use of a ceramic material that is sensitive to temperature changes. More precisely, a 3D-printed ceramic structure is heated to a specific temperature, which triggers the transformation in the material, causing it to change shape or properties. With the combination of design and material concept, this deformation can be achieved in specific applications such as twisting, folding, and self-healing.

Electrical stimuli: Ceramic materials like piezo demonstrate a range of electrical properties, including dielectric constant, piezoelectricity, and ferroelectricity. Those characteristics give the materials the potential for application in electronic components such as capacitors, sensors, and transducers.

Magnetic stimuli: The manipulation of ceramics through magnetic influence can be done by integrating magnetic particles into the ceramic ink, which can be oriented or positioned by a magnetic field. This technique can be utilized for various purposes, such as for shape-shifting, where ceramic structures can be programmed to bend, turn, or expand when subjected to a magnetic field. A specific orientation is achieved by regulating the arrangement of magnetic particles within the ceramic structure. Additionally, the combination of magnetic particles with other materials, such as polymers or gels, can produce ceramic-based magnetic actuators that expand or contract in response to a magnetic field, enabling the creation of micro- or nanoscale devices with controllable motion. Magnetic-responsive ceramics can also be developed as sensors, detecting changes in the strength or orientation of a magnetic field. For instance, ceramic sensors can detect the position or movement of a magnetic object or monitor variations in the Earth's magnetic field. Ceramics with high magnetic permeability can act as magnetic shields, redirecting or absorbing magnetic fields. For example, ceramic shields can safeguard delicate electronic devices from interference from magnetic fields.

Light: The manipulation of ceramics through 4D printing can be regulated by means of light. This is implemented utilizing substances that display photo-responsive characteristics. To illustrate, it is possible to devise ceramic configurations that transform in form or hue upon being subjected to light of a particular frequency or magnitude.

Moisture: Ceramics that react to moisture can be produced by adding hydrogels or other materials that absorb water to the ceramic ink. These ceramics can be engineered to either expand or contract as humidity levels fluctuate, resulting in the development of ceramics with the ability to change shape or actuate in a particular way.

pH: Utilizing substances tht have pH-sensitive behavior, ceramics may be made to react to pH variations. Ceramics, for instance, can be made to change mechanical or optical characteristics when exposed to solutions with different pH levels.

RESEARCH AREAS AND APPLICATIONS OF 4D PRINTING

The technological advancement of 4D printing presents a vast array of possibilities across diverse fields by utilizing the capabilities of 3D printing technology in combination with its unique fourth dimension of time. The 4D printing technology facilitates the production of entities capable of dynamically adjusting their shape, properties, and functionality in reaction to the influences presented from the external or internal stimulus. From biomedical implants that adapt to the body's needs to self-assembling structures in architecture, responsive packaging, soft robotics, and energy-efficient systems, 4D printing opens up possibilities for more adaptable, efficient, and innovative solutions in industries ranging from healthcare and aerospace to fashion and infrastructure The concept of 4D printing has revolutionized manufacturing, design, and functionality which led to the advancement in paving the way for the development of intelligent, self-adjusting materials and structures, that could exhibit remarkable abilities to confront complex challenges and improve human experiences.

Applications in Biomedical and Healthcare

The medical industry has benefited tremendously from 4D printing technology. 4D printing has extended its advancement in the medical industry from implants and tissue engineering to drug delivery, surgical probes, and bioprinting. Bioprinting has various benefits over traditional tissue engineering, including high precision in cell positioning, the capacity to build tissues with high density, and the potential to produce large tissue-engineered structures (Murphy et al, 2014). 4D bioprinting is promising for building cell-laden constructs (bio constructs) with complex geometries and functions for tissue/organ regeneration applications. Researchers have developed a single-component jammed micro-flake hydrogel (MFH) system as a cell-laden bio-ink for 4D living cell bioprinting applying for the formation of a 4D cartilage-like tissue (Ding et al, 2022). 4D bio-printing has been used to print complicated tissue structures (such as bone grafts) with the enhancement and improvement in both osteoinductive and osteoconductive properties (Pati et al, 2015). Cancer reconstruction implants have also been greatly impacted by 4D printing technology, where 4D printed samples have fewer side effects than current breast reconstruction methods, allowing the patient to have an easier recovery. The versatility of 4D printing fabrication has permitted the printing of biomedical devices, with most research focusing on stents, splints, braces, and aligners because of the high demand for outpatients since this could be customized with enhancing all parameters like whose length, diameter, thickness and other factors at the University of Michigan, in 2015 medical department used a 4D printed device for treating patients with respiratory difficulties. This polycaprolactone device, custom-made for each patient, can be created to adjust to the patient and can quickly outgrow the implants. Other applications like 4D printing stents have also give a remarkable advancement in the medical industry where the smallest stent was 4D printed using shape memory polymer for treating urethral strictures where it widens on the area helping the strictures Vascular endoprosthesis (stents) and other 4D parts that react to body heat and expand to fit the patient's needs may be printed in the future (Shim et al, 2012; Faulkner-Jones et al, 2013; Yoneyama et al, 2008). Some other applications include drug delivery (Villar et al, 2011; Villar et al, 2013; Stoychev et al, 2011; He et al, 2006). There is enormous potential and research underway on living polymers with genetic information matured with light stimuli that will change many aspects of the medical field.

Applications in Robotics and Electronics

Robotics and electronics have been growing in importance across many industries. 4D printing is crucial in the fields of robotics and electronic applications due to its unique capabilities that surpass existing conventional methods. Unlike traditional manufacturing techniques, 4D printing allows for the creation of structures that can dynamically change shape, self-assemble, and possess programmable behavior. This offers significant advantages in robotics especially soft robotics enabling the development of adaptive robots that can adjust their physical form to navigate diverse environments and perform complex tasks like grasping, sorting, climbing or crawling, inspecting, search and rescue, and drug delivery systems. Soft robotics has been created to overcome these constraints. It can produce flexible robots and, similar to people, modify their stiffness (Ge et al, 2016; Zhang et al, 2019). Soft robotics depends on soft and clever materials like electroactive hydrogel (EAHs) (Han et al, 2018), which can react to changing environmental conditions. In the future, further development in 4D Printing robots, such as enhancing the capability of controlling the actuators and sensors with the embedding system, which could be dynamically reacted to different stimuli by adjusting their functionality based on user preferences or changing conditions.

Applications in Aerospace and Defense

Weight optimization is an important factor in the fabrication of parts for space missions. With the implementation of Additive Manufacturing, fabricating lightweight long-lasting parts with optimized geometry and lower cost has been easily achieved. 4D printing to revolutionize aerospace and defense industries can be achieved by introducing advanced functionalities, improved performance, and increased efficiency. NASA has created an intelligent metallic fabric that uses 4D printing. Because of its insulating properties, this fabric is already used for astronaut suits. It could be employed to protect spacecraft and antennae from meteorites (Tyler, 2017). Some of the other applications in the defense include UAV morphing wings, which could flex angle up to 20◦ (Hoa et al, 2022), and high-stiffness aerospace parts using SMAs and 4D printing (Ashby et al, 2004). Meanwhile, Airbus is experimenting with heat-reactive materials to cool aircraft engines.

Applications in Fashion and Textiles

In fashion and textile industries have been thriving to be stable. With conventional manufacturing cutting and sewing, the material produced a lot of waste and lengthy production time Introduction 3D printing benefitted by solving the problems faced in conventional fabrication. 4D printed textiles can have dynamic properties, such as shape-changing garments or accessories that respond to temperature or movement. 4D printing technology has emerged as a revolutionary force in the fashion and textile industry, pushing the boundaries of design, functionality, and sustainability. 4D printing opens up new possibilities for creating intrinsic designs, customization, and dynamic, transformative pattern, color, and shape with the stimuli responses. Uniforms that change color depending on the surroundings are being tested by the US military, as are uniforms that regulate sweat based on the soldier's pulse or the environment's temperature. Movement, impact, temperature, and atmospheric pressure will all be adjusted via 4D-printed shoes in four dimensions (Constantinos et al, 1999). Researchers are working on smart materials that can change shape or size in response to a thermal stimulus or hydro stimulus and are having a great influence on the development of applications in textiles. The recent invention of smart material hygromorphs, which changes the shape and size in response to water or humidity, can be applied in textile industries and could have a good impact on swimsuit wear. A variety of endeavors have already presented captivating solutions to current commercial needs, and this illustrates the technology's potential in the textile industry.

4D Printing Techniques in Ceramics Based on Applications

The market for 4D printed materials on a global scale is currently growing due to the growing need for customized products of intricate geometries that are durable, lightweight, and demonstrate multi-functional properties. Industries with high demand for 4D printing ceramics are medical, aviation, electronics, and optics. The surging popularity in medicine and medical devices is demonstrated in orthopedic implants and biomedical microelectronics such as surgical probes (Bargardi et al, 2016; Liu et al, 2018). Continued development in the aviation industry requires advanced airplane components and defense weapons. This area incorporates airplane windshields, propulsive features, such as rocket debilitate frameworks, and shielding calculations for re-entry (Meza et al, 2014; Liu et al, 2018). Electro ceramic vitality gadgets, exemplified by strong oxide electrolyzed cells, speak to a promising innovation for the generation and capacity of vitality (Meza et al, 2014; Liu et al, 2018; Dai et al, 2013). These are some of the accessible applications for the 4D printing of ceramics within the industry.

DISCUSSION AND CONCLUSIONS

The progress of 3D printing and the introduction of 4D printing has been ongoing, encompassing various aspects, including design, material, and technology. Its increasing capacity for versatile and innovative utilization is evident across diverse industries. The inclusion of "time" as a fourth dimension in the realm of 3D printing represents a notable breakthrough, giving rise to the advent and growth of 4D printing. Consequently, the implementation of 4D printing technology presents a viable solution to address many constraints associated with 3D printed structures.

The extent and variety of academic literature on 4D printing comprehensively cover a wide array of important facets, namely materials, technologies, applications, and stimuli, in a largely homogenous manner. This paper presents a novel framework to enhance readers' understanding of 4D printing and facilitate future research efforts.

The study performed on this topic and analysis of relevant literature reveals a lack of data and organized information in 4D printing using ceramics. Consequently, this review incorporates new information that contributes to the future of 4D printing of ceramics within the context of a framework, which should help future research and initiatives. From this framework perspective, we identified shortcomings as well as the potential of ceramic 4D printing. This is especially true for the utilization and application of shape memory ceramics. The main objective was to explore the scope of both prospective and validated works related to the 4D printing of ceramics, organized within the framework developed to guide the discourse and illustrated in the visual abstract at the beginning of the paper. The analysis was conducted from an alternate perspective, primarily focused on the application of the technology. This viewpoint was inherently interlinked by using critical factors such as design methods, material properties, technological advancements, processes, and stimuli, which are vital to the field of ceramics.

The paradigm of 4D printing of electro ceramics has substantial potential in the advancements of electronic devices that can effectively transmit energy or signals. The implementation of piezo-based ceramics in this domain presents a promising approach for further research. The combination of structural design concepts and stimulation offers the potential to implement the 4D printing of piezo ceramics endowed with diverse functionalities. Researchers have introduced the concept of shape morphology in 4D printing by developing a precursor ink with elastic properties. This advancement has paved the way for numerous potential applications, including but not limited to body armor, self-lubricating bearings, space shuttle tiles, aircraft components, fiber optics, racing car brakes, and thermal barriers.

The 4D printing of piezoelectric ceramics has shown promise for amalgamating metamaterial design principles with piezoelectric materials utilizing controlled and tailored 3D printing techniques. This alliance is expected to yield significant innovation with medical transducers, sensors, and actuators. The challenges of 3D printing, namely the utilization of materials in a higher volume ratio and the printing of complex structures without supports have been successfully addressed through the advent of solvent-based 3D printing technology. In addition, stereolithography has proven to be a highly effective printing technology in the ceramics industry due to its ability to achieve high resolution. Through the implementation of facilitated three-dimensional printing technologies, the goal of achieving four-dimensional printing of ceramics has been pursued. Furthermore, the integration of design principles with the utilization of 4D ceramic ink and the progress of bio-ceramic precursor inks will undoubtedly facilitate more progress in a financially feasible manner.

One additional challenge encountered in the realm of 4D printing with ceramics slurry is the need to devise precursor inks that are applicable to such printing techniques. However, it is suggested that a potential solution may involve adapting existing 3D printing technologies, such as vat photopolymerization, to facilitate slurry printing effectively. Implementing heat control mechanisms within the printing environment and the precise regulation of scrapper blade angles and contact points can potentially pave the way for the realization of 4D ceramic slurry printing. The convergence of the established frameworks can give rise to future investigations in 4D-printed ceramics.

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