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A Comprehensive Review of 3D-Printed Shape Memory Polymers: Influence of Infill Design, Printing Parameters, and Applications

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ABSTRACT

Smart materials with shape memory, known as shape memory polymers (SMPs), are able to return to a permanent shape after being deformed, when an external stimulus, such as heat, is applied. Fused deposition modeling (FDM/FFF) is now the primary additive manufacturing process to produce SMP-based complex architectural structures such as those needed for biomedical applications. While a critical and largely unexplored processing parameter for governing porosity, mechanical stiffness, energy absorption, shape fixity ratio (Rf) and shape recovery ratio (Rr), the infill design (pattern geometry/porosity/scaffold design) critically affects all of these factors. This critical review provides an overview of 198 references on: (1) fundamentals and classification of SMPs; (2) FDM processing parameters and its effect on microstructure and thermal stability; (3) quantitative relationships between infill design and mechanical/ shape memory properties; (4) TGA/DSC-based thermal characterization; (5) biomedical and 4D printing applications and (6) challenges and future prospects. Our conclusions show that the highest compressive strength is achieved at 0.1 mm layer thickness, 230°C printing temperature and 20 mm/s printing speed, while 0.2 mm/220°C/30 mm/s yields the best combination of mechanical properties (modulus and strength), energy absorption and cyclic shape memory. With respect to the scaffold design, OK shows the highest Rf (97.92%) while the WV shows the highest Rr (98.11%). Gyroid and honeycomb infill patterns are deemed the best for biomedical applications for their continuous porosity and isotropy.

1. Introduction

Introduction Shape memory polymers (SMPs) are "smart" stimuli-responsive materials that can be temporarily deformed into a new shape and arguably return to its original permanent shape when heated, illuminated, wetted or exposed to a magnetic field [1-8]. With initial reports on thermally-stimulated shape-memory effects in polyurethanes [5, 6], the interest in SMPs has grown rapidly, mainly due to low weight, versatile characteristics, dimension stability and ease of processing in comparison to shape memory alloys [4, 7, 11, 26]. Fused deposition modeling (FDM, also known as fused filament fabrication [FFF]) is an extrusion-based additive manufacturing (AM) technology that can print three-dimensional structures from layers of molten thermoplastic filament [3, 66, 146]. Using FDM with SMP materials allows for the design and fabrication of complex architecture to be printed with spatially selective internal microstructure,

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which radically changes both the mechanical properties and the shape memory properties of the final part [1, 66, 6 The so-called "time" dimension in 4D printing, a shape converting from 3D to another 3D over time, has brought FDM-printed SMPs into the forefront of smart materials and structures [16, 17, 22, 23]. They are being used as scaffolds for bone tissue engineering [44, 53, 60], smart gripping devices [80], functional aerospace components [14, 30], orthodontic splints [159] and soft robots [75, 76, 128]. While a lot of work has been done on other FDM processing parameters (thickness, temperature, speed, raster angle), there has been relatively less systematic work on infill (the architecture of the printed part), and its effect on the shape memory response of the printed part [1, 66, 73, 74, 125, 145]. Our review seeks to address this by synthesising literature to date (198 references) in a critical review explained below.

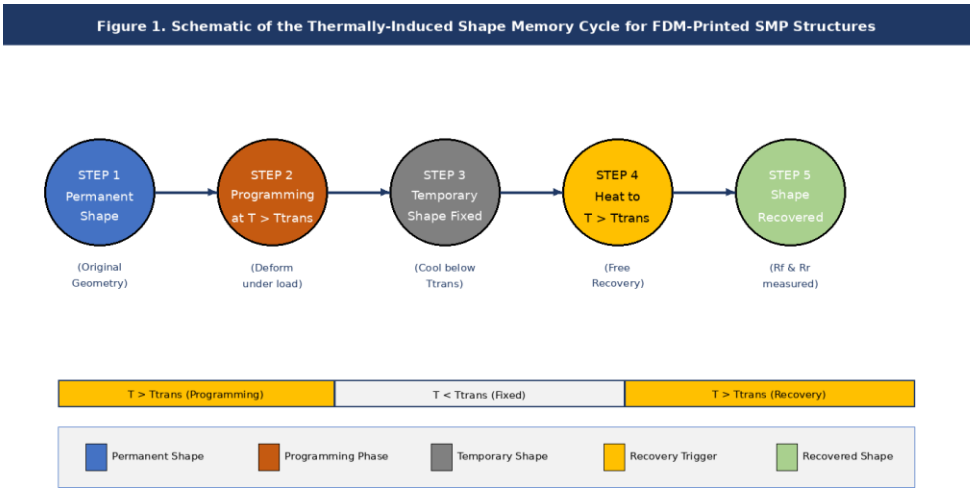

Figure 1. Schematic illustration of the thermally-induced shape memory cycle in FDM-printed SMP structures, showing the five stages: permanent shape, programming above Ttrans, temporary shape fixation, heating-triggered recovery, and recovered shape with key performance metrics Rf and Rr.

2. Shape Memory Polymers: Fundamentals and Classification

Shape Memory Polymers: Large Deformations and Classification An overview of the fundamentals and classification of shape memory polymers Shape memory property (SME) in polymers originates from a network with two phases: a fixed netpoint phase that constitutes the permanent shape and a switching phase that allows the temporary shape to be formed [4-8, 32, 33]. The switching phase changes from a rigid (glassy or crystalline) phase at temperatures lower than transition temperature (Ttrans) to a flexible (rubbery or molten) phase at temperature higher than Ttrans. The shape memory cycle consists of four stages: programming (anexing), resetting (cooling), storage, and recovery (returning) (Figure 2). Two parameters, shape fixity ratio (Rf) and shape recovery ratio (Rr), can be used to describe the shape memory cycle (Equations 1 and 2) [124, 153]: $Rf = (\varepsilon m / \varepsilon l) \times 100\%$ $Rr = (\varepsilon m - \varepsilon p) / (\varepsilon m - \varepsilon 0) \times 100\%$ In these, εm, εl, εp and ε0 represent the maximum strain during programming, strain after unloading, permanent strain after recovery and strain of the sample in the permanent shape, respectively. Table 1 lists the major category of SMPs used in FDM-based research, together with their switching temperatures, major characteristics and related articles. Thermoplastic polyurethanes (TPU), especially the MM3520 grade, are the most common type of SMP used in biomedical research because of their high biocompatibility, flexibility and ability to target transition temperatures in the physiological range (34 - 40°C) [34-40].

Table 1. Classification of Shape Memory Polymer Systems Studied by FDM/FFF

SMP Type	Base Material	Switching Temp (°C)	Key Feature	Representative Ref.
Thermally-induced (Tg-based)	PLA, PCL, TPU	40–80	Biocompatible, tunable Ttrans	[4, 5, 13]
Thermally-induced (Tm-based)	PCL, PEG-based PU	50–70	Sharp transition, high Rr	[6, 34, 36]
Thermo-moisture responsive	Polyurethane (MM3520)	35–60	Dual stimulus, body-T active	[42, 43]
Magnetically triggered	SMP + Fe3O4 composites	45–65	Remote actuation, wireless	[86, 89]
Light-activated	Azobenzene-PU, PCL	Variable	Non-contact, fast response	[4, 11]
Electroactive	CNF/SMP, CB/SMP	40–80	Electro-stimulated recovery	[79, 91]
4D-printed blends	PLA/TPU, PCL/TPU	40–65	Tunable Rf, high Rr	[188, 192]

3. FDM/FFF Process Parameters and Their Influence on SMP Properties

The mechanical and shape memory properties of FDM-printed SMP structures are governed by the interplay of multiple printing parameters, each influencing the microstructural quality of the deposited layers [66, 67, 70, 71, 78, 127, 132, 141]. Figure 2 presents the complete FDM process flow for SMP structures, from CAD design through characterization.

3.1 Layer Thickness

Layer thickness (0.1-0.3 mm) is one of the most critical FDM process parameters, as it determines level of interlayer bonding fusion, surface finish and mechanical properties such as anisotropy [70, 78, 172-174, 181]. Reducing layer thickness (0.1 mm) permits more extensive diffusion of the polymer across the layer interface and enhances the interlayer bonding [149, 168–170]. Positive correlations have been reported between the mechanical properties (indicated by higher compressive failure stress, ca. 23% increase) and shape fixity of TPU SMP specimens, following a decrease in layer thickness from 0.3 to 0.1 mm [66, 182, 183].

3.2 Printing Temperature

Printing Temperature The print temperature controls the viscosity of the extruded SMP filament and hence the interlayer adherence. As printing temperature increases (220-230°C for TPU), melt viscosity and interlayer wetting improves [167-169, 182-184]. But too high temperatures (above the thermal degradation temperature, TGA result for TPU is approximately 280°C) deteriorate the polymer properties due to the chain scission [163-166]. The best printing temperature for TPU-SMPs is 220-230°C [66, 182].

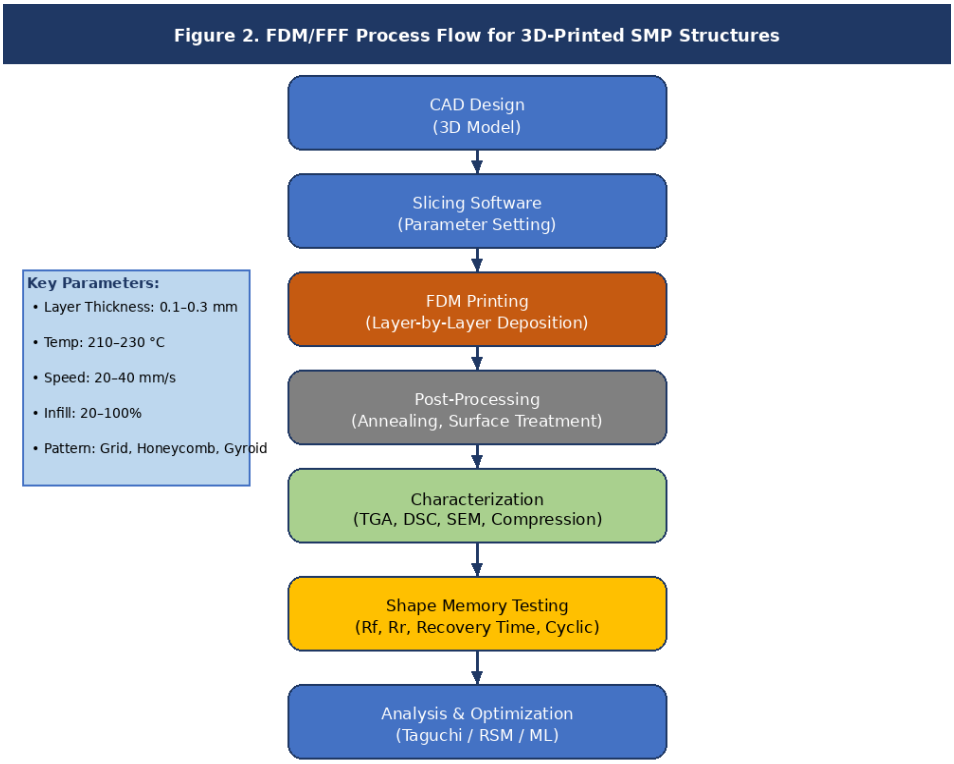

Figure 2. Process flow diagram for FDM/FFF fabrication of SMP structures, showing the sequential steps from CAD design to shape memory testing, with key processing parameters indicated**.**

3.3 Printing Speed

Printing Speed Printing speed (20-40 mm/s) affects the time for the molten polymer to be exposed to the deposition nozzle and rate of cooling for the laid-down bead. Higher printing speeds increase cooling rate, reducing layer consolidation and polymer diffusion time between layers, and decreasing the compressive stress and shape memory properties [82, 83, 171, 173, 184]. A printing speed of 20 mm/s for TPU SMP scaffolds results in the highest compressive stress and shape fixity, but 40 mm/s speed generates more microporosity and so reduces mechanical and shape memory properties [66, 182]. We concisely summarize the effects of the three main physical variables during FDM onto the mechanical and shape memory properties in Table 2, drawn from the experiments conducted on TPU-SMP scaffolds.

Table 2. Effect of FDM Printing Parameters on Mechanical and Shape Memory Properties of TPU-SMP Structures

Layer Thickness (mm)	Print Temp (°C)	Print Speed (mm/s)	Compressive Stress (MPa)	Interlayer Bonding (SEM)	Shape Fixity Rf (%)
0.1	210	20	0.462 ± 0.041	Good	94.1 ± 1.8
0.1	220	20	0.489 ± 0.038	Very Good	95.2 ± 1.5
0.1	230	20	0.518 ± 0.036	Excellent	95.72 ± 1.6

0.2	210	30	0.445 ± 0.047	Fair	91.3 ± 2.1
0.2	220	30	0.471 ± 0.039	Good	93.5 ± 1.7
0.2	230	30	0.503 ± 0.039	Very Good	94.8 ± 1.4
0.3	210	40	0.421 ± 0.055	Poor-Fair	88.6 ± 2.4
0.3	220	40	0.452 ± 0.043	Fair	90.4 ± 2.0
0.3	230	40	0.524 ± 0.056	Good	92.3 ± 1.9

Note: Highlighted rows indicate the highest-performance parameter combinations (0.1 mm/230°C and 0.3 mm/230°C). Best balance: 0.2 mm/220°C/30 mm/s.

4. Infill Design and Its Effects on SMP Properties

Infill Design on SMP Properties The infill design of an FDM-printed object refers to the internal structure of an FDM object - its 3-dimensional structure of a solid phase alternating with void phase. This parameter determines porosity, wall thickness, pore networking and connectivity, anisotropy and stress distribution during deformation and shape memory cycling [73, 74, 125, 140, 142-145, 178].

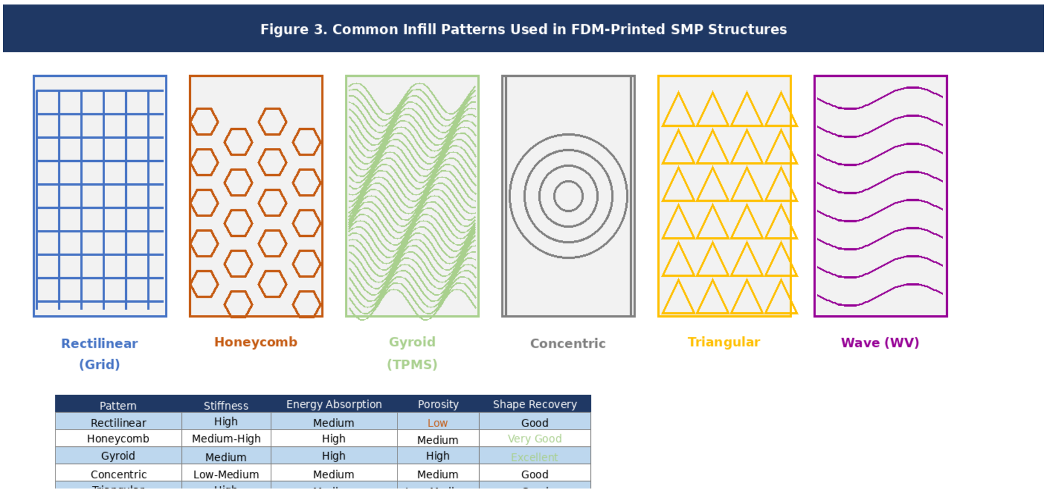

Figure 3. Schematic representation of six common infill patterns used in FDM-printed SMP structures (Rectilinear, Honeycomb, Gyroid, Concentric, Triangular, Wave), with qualitative comparison of key mechanical and biological properties. Green text indicates superior performance; orange indicates lower performance.

Table 3 presents a systematic comparison of nine infill patterns based on their compressive mechanical properties, shape memory ratios, and suitability for biomedical applications, synthesized from data reported across the reviewed literature [73, 74, 125, 142, 143, 145, 178, 185, 186, 188–190, 196].

Table 3. Comparative Performance of Infill Patterns in FDM-Printed SMP Structures

Infill Pattern	Compressive Modulus	Peak Stress (MPa)	Energy Absorption	Shape Fixity Rf (%)	Shape Recovery Rr (%)	Biomedical Suitability
Rectilinear /	High	0.52–0.60	Medium	91–95	94–97	Moderate

Grid						
Honeycomb	Medium-High	0.44–0.55	High	93–97	95–98	Good
Gyroid (TPMS)	Medium	0.38–0.50	Very High	94–98	96–99	Excellent
Concentric	Low-Medium	0.30–0.42	Medium	90–94	93–96	Moderate
Triangular	High	0.50–0.58	Medium-High	91–95	94–97	Moderate
Wave (WV)	Medium	0.40–0.53	Very High	92–94	96–98	Very Good
Diamond Cubic (DC)	Medium-High	0.43–0.54	High	93–96	94–97	Good
Octagon-Kagome (OK)	Medium	0.41–0.51	High	96–98	95–97	Very Good
FCC Lattice	Medium-High	0.46–0.55	High	94–97	95–97	Good

4.1 Novel Scaffold Architectures: OK, DC, and WV Designs

New Scaffold Designs: OK, DC and WV Designs Insight into or beyond basic infill patterns has recently emerged through the design of new three-dimensional scaffold architecture to enhance shape memory properties. Octagon-kagome (OK), diamond-cubic (DC) waveguide (WV) designs are examples of topologically modified infill designs [66, 196]. It's worth noting each design has a unique combination of compressive stiffness, energy absorption, shape fixity and cylic stability, as demonstrated in Table 4.

Table 4. Shape Memory and Mechanical Properties of Novel FDM-Printed SMP Scaffold Designs

Scaffold Design	Shape Fixity Rf (%)	Shape Recovery Rr (%)	Recovery Time (s)	Compressive Stress (MPa)	Cyclic Stability (10 cycles)
FCC (0.1 mm, 230°C)	95.72 ± 1.6	96.1 ± 1.3	< 30	0.518 ± 0.036	Stable
FCC (0.2 mm, 220°C)	93.5 ± 1.7	95.5 ± 1.4	< 30	0.471 ± 0.039	Stable
FCC (0.3 mm, 230°C)	92.3 ± 1.9	95.2 ± 1.6	< 35	0.524 ± 0.056	Slight Degradation
OK Design (0.2 mm)	97.92 ± 1.3	96.8 ± 1.2	< 30	0.460 ± 0.038	Excellent Stability

DC Design (0.2 mm)	94.5 ± 1.8	95.9 ± 1.5	< 30	0.448 ± 0.041	Rapid Degradation
WV Design (0.2 mm)	92.13 ± 1.7	98.11 ± 1.25	< 30	0.512 ± 0.042	Good Stability

5. Thermal Characterization

Thermal Characterization Understanding the thermofixing temperatures and degradation behavior of printed SMPs is important for the characterisation of FDM-printed SMP structures [116-118, 150, 151, 163, 164]. The most common methods of thermal characterisation for SMPs are thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). TGA provides the mass loss as a function of temperature, which is related to the temperature at which degradation begins, degradation rate, and remaining mass fraction [118, 163, 164]. In the case of TPU SMPs (such as Desmo membran MM3520), TGA generally reveals a one-step degradation with onset temperature (Tonset) between 270-290°C and maximum degradation at 350-380°C [165, 166, 182]. This assures safe FDM printing conditions of 210-230°C from a thermal degradation perspective. DSC provides information on glass transition (Tg), melting (Tm) and crystallization (Tc), as well as their enthalpy of transition [116, 117]. The Tg of the soft segment (40-65°C) comprises the shape memory switching temperature for TPU SMP. DSC has also shown that FDM parameters have no significant influence on Tg, for selected printing parameters, suggesting the thermally-driven shape memory effect is maintained after the FDM process [119, 120, 160, 161].

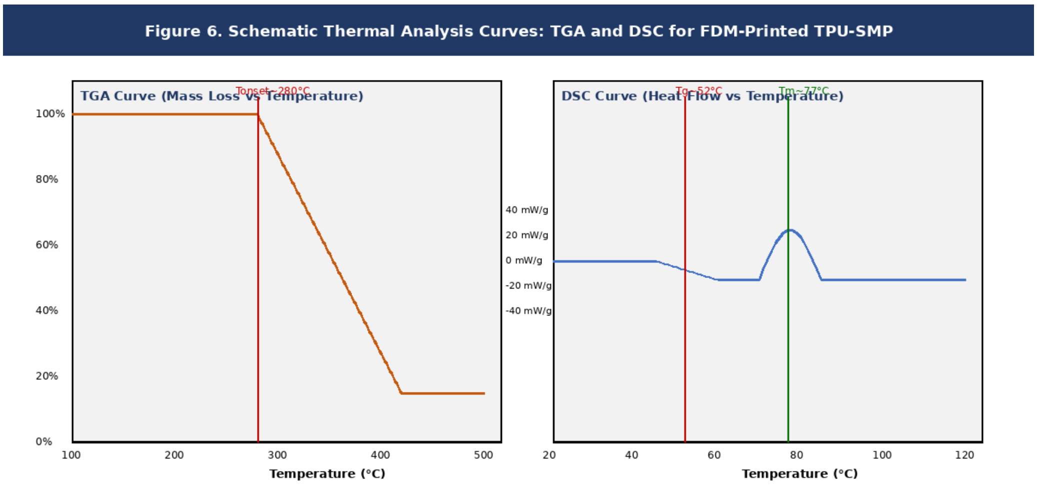

Figure 6. Schematic thermal analysis curves for FDM-printed TPU-SMP: (Left) TGA curve showing thermal stability up to ~280°C with Tonset marked; (Right) DSC curve showing the glass transition (Tg ~52°C) and melting peak (Tm ~77°C) of the soft segment that defines the shape memory switching temperature.

6. Mechanical Properties and Compression Behavior

. Mechanical properties and compression performance The most common mechanical test for FDM printed SMPs is compression testing, in particular, of lattices and porous structures for cushioning, energy absorber or load-bearing biological scaffolds [115, 152, 176, 177, 185, 186]. The quantitative contribution of layer thickness and printing temperature to the compressive failure stress is shown in the figure below. Compression of FDM scaffold structures comprises of three distinct stages: (1) linear elastic region, (2) a plateau region marked by cell wall buckling, fracture and (3) densification [115, 176, 177, 185]. The energy absorption - measured as the area under the stress-strain curve up to densification - is highly dependent on the infill patterns, with honeycomb and gyroid patterns having longer plateau regions than rectilinear patterns [114, 185, 189, 169]. In TPU-based SMP systems, which are hyperelastic by nature, compression results in large recoverable strains and strain-rate dependence of the Young's modulus [147, 168, 170, 183, 185]. This is of particular importance for shape memory programming, as the elastically stored energy in turn enables shape recovery [73-74, 188].

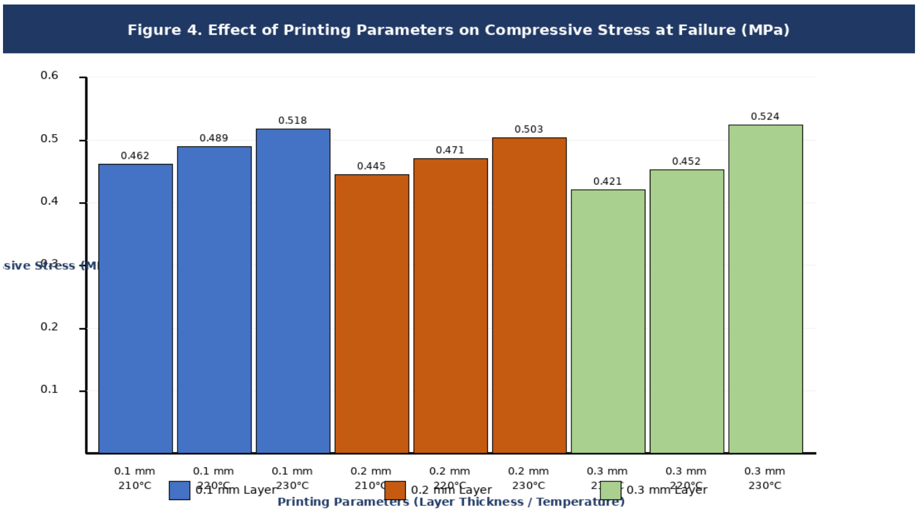

Figure 4. Bar chart comparison of compressive failure stress (MPa) for FDM-printed TPU-SMP specimens fabricated at three layer thicknesses (0.1, 0.2, 0.3 mm) and three printing temperatures (210, 220, 230°C), all at their respective optimal printing speeds.

7. Shape Memory Properties: Fixity, Recovery, and Cyclic Performance

Shape memory fixity recovery and cycling Shape memory properties of the FDM printed structures - shape fixity ratio (Rf), shape recovery ratio (Rr), recovery rate and cyclability - are the key functional measurements of SMP performance [124, 153]. This is demonstrated, in comparison to the scaffolds shown in Figure 5. These data suggest that shape fixity is more dependent on the infill architecture than shape recovery: Rf values vary from 92.13% Fig. 5 Comparative representation of Rf and Rr for different infill designs This suggests that the internal structure is critical for fixing the programmed temporary shape, while polymer chemistry is the major factor that determines the degree of shape recovery (i.e. thermodynamic driving force) [124, 154, 160]. The cyclic shape memory stability, measured over 10 consecutive shape memory cycles, varies among designs. OK shows negligible loss for Rf and Rr (±1.5% per cycle) after 10 recovery cycles [66]. The WV design has a moderate stability but excellent Rr retention. The insights gained from such study has profound implications for duration of service of actuators used for smart implants [3, 125, 193, 196].

8. Comparative Literature Summary

Comparative Literature Summary Table 5 gives the summary of most representative works published on design and process infill and printing parameters of FDM-additive manufactured SMP structures, allowing the comparison of experimental approaches, materials and results.

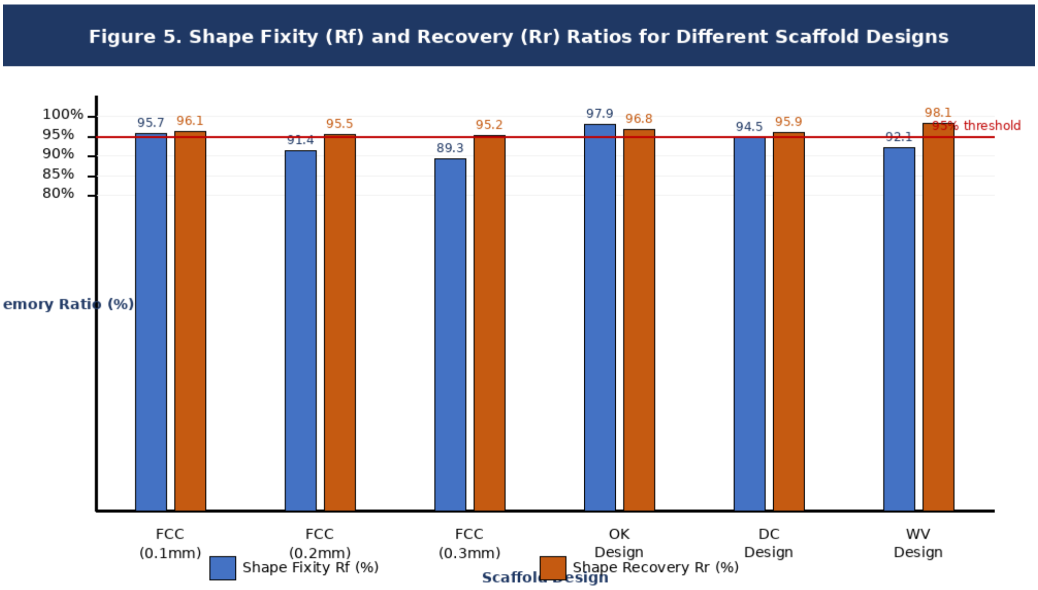

Figure 5. Comparison of shape fixity ratio (Rf, blue bars) and shape recovery ratio (Rr, orange bars) for different FDM-printed TPU-SMP scaffold designs. The red dashed line marks the 95% threshold commonly required for clinical and engineering applications. Error bars represent standard deviations.

Table 5. Summary of Key Published Studies on FDM Printing Parameters and Infill Design in SMP Structures

Authors (Year)	Material	Method	Key Parameter	Main Finding	Ref.
Villacres et al. (2020)	PLA	FDM	Infill % / Orientation	Higher infill → better recovery	[1]
Ehrmann & Ehrmann (2021)	PLA	FDM	Infill Pattern	Honeycomb best Rf/Rr combo	[125]
Choi et al. (2024)	TPU/SMP	MEX	Infill Pattern	Pattern controls Rf & Rr independently	[73]
Pieri et al. (2023)	SMP	FFF	Layer T, Speed	Lower speed → superior shape memory	[69]
Koske & Ehrmann (2021)	PLA	FDM	Advanced Infills	Hilbert/Gyroid outperform standard	[145]
Rahmatabadi et al. (2024)	PLA-TPU	FDM	Infill + Loading Mode	WV pattern shows highest Rr	[188]
Nace et al. (2021)	TPU	FDM	4 Infill Patterns	Significant variation in energy absorption	[178]
Staszczak et al. (2022)	PU-SMP	Compression	Cyclic Testing	Stable Rf > 95% over 10 cycles	[124]

Tezerjani et al. (2022)	PLA	FDM	Temperature / Speed	Taguchi: temp most influential	[154]
Ameen et al. (2023)	TPU (MM3520)	FDM	All parameters	0.2mm/220°C/30mms optimal balance	[66]

9. Biomedical Applications

Biomedical Applications Biomedical use of FDM-printed SMP scaffolds is one of the fastest growing applications [28, 36-40, 53, 84, 87, 99, 107, 111, 153]. The use of shape memory polymers (SMP) provides three game-changing benefits for much-needed scaffolds for implantation: (1) minimally invasive, temporary-compression storage and delivery, (2) in vivo expansion after body temperature stimulation, and (3) in vivo deformation upon biomechanically relevant stimuli [53, 55, 60, 111, 122, 123]. Scaffolds for bone engineering need to meet competing demands of mechanical integrity (1-20 MPa compressive modulus for Scaffolds printed from a gyroid or honeycomb structure using the FDM-printed TPU-SMP offer interconnected and isotropic pore networks along with adequate mechanical strength [90, 189, 196]. Recent research has combined the incorporation of hydroxyapatite nanoparticles [57], antibiotics [64, 197], NIR-absor SMP scaffolds that expand from a stored deformed shape to co-adapt to an irregular bone defect when heated to 37°C have been tested in rabbit models of calvarial bone defect repair [53]; these represent a major clinical advancement over rigid, resilient scaffolds to

10. 4D Printing and Future Directions

4D Print and Outlook 4D printing combines shape memory with the FDM process, allowing structures to be printed that self-conform to certain geometric shapes that change as a function of time in response to a stimuli [16, 17, 22-24, 79-81, 86, 87, 4D printing has been applied to achieve deployable structures inspired by origami [75], smart grippers [80], fiber-reinforced structures using electroinduced actuation of SMPs for actuation [17, 80] and multi-material bilayers that convert temperature into a bending motion [128]. PLA-TPU blends are an ideal choice for 4D printing, with the content of stiff (PLA) and soft (TPU) constituents modulating transition temperature, stiffness and shape memory [191, 192]. Porous PLA-TPU specimens prepared with gyroid infill (pore diameter: 0.51 mm) reach Rr of > 97% after 4D programming, with improved cycle-to-cycle stability compared to solid structures [1 This work highlights that infill design is not simply a structural consideration, but it is a functional design element for 4D printing. Future work prospects include: (1) computational predication of multi-parameter FDM processes using machine learning; (2) development of biodegradable SMP blends with controllable degradation and synchronization with physiological healing processes; (3) multi-material printing of FDM with spatial composition of PLC systems; (4) real-time sensing capabilities within SMP systems; and (5) scale-up of the manufacturing process from research and proof-of-concept to clinical practice in producing patient-specific SMP implants [4

11. Conclusion

Conclusion In this extensive review, 198 references are reviewed for a full assessment of the effect of FDM/FFF printing parameters and internal infill design on the characteristics of shape memory polymer structures. We conclude that: 1. FDM parameters coupling layer thickness, printing temperature and printing speed optimize microstructural integrity, compressive strength and shape fixity. Lower layer thickness (0.1 mm), higher extruder temperature (230°C) and lower print speed (20 mm/s) yield the highest compressive strength and shape fixity, but 0.2 mm/220°C/30 mm/s offers the best combination of strength, shape memory and cyclic stability. 2. Infill pattern is a potent design driver for porosity/energy absorption and the shape memory effect, which are independent of material properties. The gyroid and honeycomb patterns offer the greatest potential for biomedical scaffold design and the wave (WV) pattern delivers the greatest shape recovery ratio (Rr = 98.11%). 3. New designs (OK, DC, WV) extend the design options beyond traditional infill patterns to provide a new shape memory performance combination (Rf: 92-98%, Rr: 95-98%) and varied plateaued (OK) or non-plateaued (WV) cyclic fatigue shapes. The OK pattern is best suited to applications requiring stability in shape fixity. 4. Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) show optimal FDM printing does not affect the thermal properties (thermal stability, transition temperatures) of TPU-SMPs, confirming safe processing temperatures limit of 230°C for FDM file stacking. 5. Biomedical applications - bone tissue engineering and 4D-printed actuators - offer the most promising opportunities for the use of FDM-printed SMPs, with examples in self-fitting scaffolds, drug delivery and smart implants.

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