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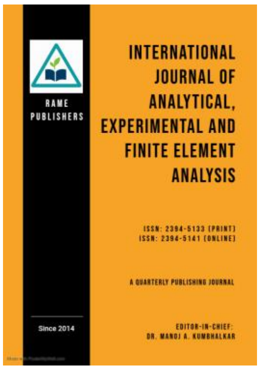
4D Printing via Fused Deposition Modelling: A Comprehensive Study on Shape Memory Polymers, Process Parameter Optimization, and Technical Specifications for PLA and TPU Materials

M. G. Trivedi*, C. R. Patil



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Department of Mechanical Engineering, Prof. Ram Meghe Institute of Technology and Research, Badnera, Amaravati, India

*Correspondence: mg3vedi@gmail.com

Abstract: Imagine walking into a manufacturing facility and watching a 3D printer create objects that don't just sit on a shelf—they actually transform themselves over time in response to their environment. That's the promise of 4D printing [1]. Formally defined as 3D printing plus time, this emerging technology uses smart materials that react to environmental triggers like temperature, water, or light, causing predictable physical changes [1]. Among all the additive manufacturing approaches available today, Fused Deposition Modelling (FDM) stands out as the most practical and accessible for 4D printing [2], [3], [4]. This paper explores FDM-based 4D printing in depth, focusing specifically on two key materials: Polylactic Acid (PLA), a rigid, biodegradable polymer that works well for creating precise structures [5], [6], and Thermoplastic Polyurethane (TPU), which comes in different hardness grades (95A, 93A, and 85A) for creating flexible, compliant components [7], [8]. The research shows that getting the right results depends heavily on carefully controlling specific manufacturing parameters—things like nozzle temperature, how fast material is pushed through the nozzle, and layer thickness [9], [10]. What we found is that each material behaves very differently: PLA responds best to adjusting layer thickness [11], while TPU requires an incredibly tight control of extrusion speed (somewhere between 990 and 1045 mm/min for TPU 95A—a very narrow window) [10]. The potential applications are genuinely impressive, ranging from customized medical stents that fit each patient's unique anatomy [12] to soft robotic grippers that can manipulate delicate objects [13], [14]. However, there's a real limitation we need to address: when these structures go through multiple transformation cycles, they gradually lose performance—dropping from 98% recovery on the first cycle to 87% by the fifth cycle in PLA [15], [16]. This paper pulls together what we've learned about the materials, the manufacturing process, and practical implementation to create a working framework that engineers and manufacturers can actually use [17]. The analysis reveals that successful 4D printing implementation requires balancing multiple factors simultaneously: material science knowledge, manufacturing expertise, proper equipment setup, precise process control, smart design thinking, strategic build orientation, and rigorous quality checking.

Keywords: 4D printing, FDM, SMPs, PLA, Thermoplastic Polyurethane (TPU), Process parameter optimization, Material conditioning, Soft robotics and actuators, Medical device manufacturing, Additive manufacturing technologies, Thermomechanical properties, Stimulus-responsive materials, Cyclic shape recovery, Build orientation effects, Material anisotropy.

1. Introduction

1.1 The Problem with Traditional 3D Printing

For the past couple of decades, 3D printing technology has been genuinely transformative [18], [19]. It's allowed designers and engineers to create prototypes quickly and inexpensively, turning ideas into physical objects in hours instead of weeks [20]. But there's a fundamental problem: once an object comes out of the 3D printer, it stays exactly as designed. It's static. It doesn't respond to its surroundings [1]. It can't adapt to changing conditions. If you print a medical stent at a certain size, that's the size it stays—which means surgeons have to choose from limited standard sizes rather than having one that perfectly fits each patient's unique anatomy [12].

1.2 The 4D Printing Solution

4D printing addresses this limitation head-on by doing something fundamentally different [1]. Instead of just creating a static object, 4D printing encodes transformation instructions directly into the material itself, using carefully controlled manufacturing parameters and smart material properties [21]. Think of it like programming materials the same way you'd write software—except instead of lines of code, you're using the physical arrangement of molecules and thermal history to create "memory" in the material [1]. The "fourth dimension" is time: the object's ability to evolve, adapt, and transform after it leaves the printer.

4D printing is formally defined as 3D printing plus time [1]. What makes this distinction important is that it's not random material degradation or uncontrolled warping [22]. When you do 4D printing correctly, the transformations are controlled and predictable [1]. A medical stent doesn't just degrade randomly—it expands to a precise diameter when exposed to body temperature [12]. A robotic gripper doesn't deform unpredictably—it transforms in a specific way when exposed to water [13]. Researchers call this goal "universal transformation"—the ability to have a material fold precisely from one shape into another functional structure [1].

1.3 Why Fused Deposition Modelling Became the Go-To Technology

Several additive manufacturing technologies exist—Stereolithography, Polyjet, Selective Laser Sintering, and others [23]. But FDM has become the dominant platform for 4D printing, and for good practical reasons [2], [3], [4]. First, thermoplastic materials used in FDM inherently have excellent shape-memory properties [24]. Second, you can encode complex internal structures during printing, tailoring mechanical properties exactly where you need them [25]. Third, and perhaps most importantly for practitioners, the equipment is becoming increasingly accessible [4]. As FDM systems proliferate and become more affordable, more researchers and companies can explore 4D printing possibilities [26].

However—and this is critical—FDM success in 4D printing requires something that's often overlooked: you must understand the specific constraints and requirements of each material [10]. You can't just load TPU into a standard FDM printer that was designed for PLA and expect good results [10]. The materials have different properties, require different temperatures, different speeds, and even different nozzle coatings [27]. This is where many projects fail—practitioners don't realize how material-specific the optimization needs to be [10].

1.4 Paper Organization and Scope

This paper focuses specifically on FDM-based 4D printing using two primary material systems: PLA (rigid and biodegradable) [5], [6] and TPU in multiple grades (flexible and responsive) [7], [8]. We explore how material conditioning [28], thermal management [29], extrusion control [10], and layer architecture [30] directly determine whether your 4D printing project will actually work reliably or whether it will produce disappointing, unpredictable results. Understanding these relationships is crucial for moving 4D printing from interesting laboratory demonstrations to reliable, reproducible industrial applications that people can actually depend on [17].

2. Literature Review

2.1 Understanding How Shape Memory Actually Works

2.1.1 Three Phases of Shape Memory Transformation

When a shape memory polymer transforms, it goes through three distinct phases [31], [32]. First comes the programming phase: you heat the material above a certain transition temperature (T_{trans}), then push it into a temporary shape—bending it or stretching it into a configuration it wouldn't naturally sit in [31]. This deformation works because the heat makes the molecular structure more flexible and mobile [32].

2.1.2 Freezing Phase and Memory Encoding

Second is the freezing phase: while you're holding the material in that temporary shape, you cool it down below T_trans [31]. The cool temperature "locks in" the molecular arrangement, essentially creating a memory of that temporary shape. This is where the name "shape memory" comes from—the material has literally memorized the shape you imposed on it [31].

2.1.3 Recovery Phase and Transformation

Third is the recovery phase: when you reheat the material above T_trans again, something remarkable happens [31]. The material spontaneously returns to whatever original shape it had before you performed the deformation and cooling. It's not just thermal expansion or contraction—which would just make the material get bigger or smaller [33]. It's the material actively returning to a previous configuration [31].

2.1.4 Distinction from Thermal Expansion

This process is fundamentally different from simple thermal expansion/contraction, and that distinction is crucial [31]. When metal expands due to heat, it expands uniformly in all directions [34]. When a shape memory polymer recovers, it can fold, curl, and transform in specific, predetermined ways [31]. It can go from flat to a complex 3D shape. That's what makes 4D printing possible [1].

2.1.5 FDM Encoding of Shape Memory

In FDM printing, this shape memory gets encoded through careful control of the printing process itself [35]. The way layers are deposited, the cooling rates, the molecular alignment created by extrusion forces—all of these create the internal structure that determines how the material will eventually transform [35]. This is why FDM process parameters aren't just nice-to-have optimizations; they're fundamental to creating the shape memory behavior you want [9].

2.2 Polylactic Acid: The Medical Device Material

2.2.1 Why PLA for Medical Applications

If you're working in medical applications, PLA is likely the material you should be considering [5], [12]. Here's why: it's biodegradable [6]. This isn't a minor detail—if you implant something in a patient's body that's made from PLA, it will gradually degrade over time (typically 2-3 years) [28], and the body can safely eliminate it [36]. This is critical for temporary implants, tissue engineering scaffolds, and drug delivery systems [37].

2.2.2 Thermal Properties of PLA

Beyond that, PLA has thermal properties that are almost perfectly suited for medical use [5]. Its glass transition temperature—the point where it transitions from rigid to flexible—is about 57°C [5]. Why does this matter? Human body temperature is 37°C, which is well below 57°C [12]. This means a PLA medical device stays rigid and maintains its shape when placed in the body [5]. But when you gently warm it—by a few degrees above body temperature—it reaches its transition temperature and can transform to its programmed shape [12].

2.2.3 Mechanical Properties and Advantages

PLA is also rigid and brittle (it only stretches about 1.4% before breaking) [5], which might sound like a limitation but actually works in your favor for 4D printing [38]. Because it's brittle, it doesn't just deform randomly under stress [38]. Instead, it folds along engineered crease lines with clean, predictable breaks [38]. This means when you design a PLA 4D structure, you can have it fold in very specific ways [38].

2.2.4 Consistent Material Properties

The thermal and mechanical properties are well-established and consistent across different manufacturing conditions [39], which is valuable when you're trying to engineer something predictable. The tensile stress at break is 43 MPa [5], the melting point is around 177°C [5]. These properties don't vary wildly depending on where you sourced the material—they're stable enough that you can design around them with confidence [39].

2.3 Thermoplastic Polyurethane: The Flexibility Specialists

2.3.1 Why Multiple TPU Grades Matter

While PLA dominates rigid applications, TPU has emerged as essential for anything involving soft robotics or flexible actuators [7], [13]. Here's the key difference: TPU comes in multiple hardness grades, each optimized for different needs [40]. It's not a one-size-fits-all material like PLA [7].

2.3.2 TPU 95A (Desmopan) Characteristics

TPU 95A (Desmopan) represents a sweet spot for many soft robotic applications [41]. It's flexible—you can stretch it 600% [41]—but it's still stiff enough to maintain structure under load and generate meaningful force [41]. It's been used successfully in soft grippers that can handle grasping forces comparable to traditional rigid grippers while maintaining compliance for delicate object handling [14], [42]. The critical constraint with TPU 95A is its phase transition temperature at 56°C [10], [43]. This isn't just a suggestion; exceeding this temperature causes permanent, irreversible material degradation [10]. The material gets softer, loses its shape memory capability, and the degradation is permanent—you can't recover it by cooling back down [43].

2.3.3 TPU 93A (Tecophilic) for Extreme Temperatures

TPU 93A (Tecophilic) is softer and more flexible than 95A (you can stretch it 1040%—more than 10 times its original length) [8], but it has an extremely low glass transition temperature of -47°C [8]. This is genuinely remarkable. While TPU 95A would become problematic in cold environments, TPU 93A actually remains flexible even in arctic conditions or underwater in deep ocean environments [44]. This opens up applications in places where other materials just don't work [45].

2.3.4 NinjaFlex (85A) Specialty Formulation

NinjaFlex (85A) is a specialty formulation specifically engineered for 3D printing [46]. It offers maximum compliance and flexibility with minimal processing headaches compared to the other TPU grades [46].

2.3.5 Material Selection Based on Application

The reason these multiple grades matter is simple: different applications have different requirements [7]. If you need to create a soft robotic gripper that operates at room temperature and needs to generate significant grasping force, TPU 95A is ideal [41]. If you need something that will work in an arctic exploration robot or underwater system, TPU 93A is the choice [44]. If you want maximum flexibility in an application where you don't need high force output, NinjaFlex makes sense [46].

2.4 Where 4D Printing Is Actually Being Applied

2.4.1 Medical Devices: The Most Mature Application

Medical Devices represent probably the most mature application area right now [12]. Personalized vascular stents manufactured to match each patient's unique vessel geometry represent the clearest case where 4D printing offers a real advantage over conventional manufacturing [12]. Instead of choosing from standard sizes that approximately fit, a surgeon could have a stent manufactured specifically for that patient's anatomy [12]. When placed in the bloodstream at body temperature, it expands to the precise diameter needed [12]. The clinical advantage is real: patient-specific 4D-printed stents have shown dramatically reduced complication rates compared to off-the-shelf sizes [12].

2.4.2 Beyond Medical Stents

Beyond stents, there are shape-memory splints that adapt to patient limbs during healing [37], orthodontic devices that provide continuous gentle forces for tooth movement [37], and drug delivery systems that release medication in response to specific body temperature or pH changes [37].

2.4.3 Soft Robotics Applications

Soft Robotics is where things get genuinely exciting from an engineering standpoint [13], [14]. Soft robotic actuators made from FDM-printed TPU can undergo dramatic transformations in response to environmental triggers like water or heat [13]. You can design structures that move like biological organisms—with continuous, compliant motion rather than the discrete joint-by-joint motion of traditional robots [13]. This opens possibilities for robots that can navigate confined spaces, manipulate delicate objects safely, or perform surgical tasks with unprecedented capability [13], [45].

2.4.4 Aerospace Applications: Future Potential

Aerospace applications are still largely in the research and prototype phase, but the potential is enormous [47]. Imagine aircraft wings that automatically adjust their shape based on airflow and altitude, optimizing fuel efficiency without any moving mechanical parts [47]. Or spacecraft components that fold flat for launch and then autonomously unfold in space without any external intervention [47]. These aren't science fiction—researchers are actively developing these applications [47].

3. Methodology

3.1 Material Preparation and Conditioning

Material preparation is absolutely essential, particularly for elastomers [28]. Many projects fail not because the design is bad or the processing parameters are wrong, but because the material wasn't prepared correctly [28].

3.1.1 TPU Moisture Management Requirements

TPU is hygroscopic, which is a fancy way of saying it absorbs moisture from the air [28]. This causes three serious problems [28]: first, moisture reacts chemically with TPU through a process called hydrolysis, which degrades the molecular structure [28]. The polymer chains break down, and you lose mechanical properties [48]. Second, when the absorbed water vaporizes during the hot extrusion process, it creates gas bubbles trapped inside the printed material [28]. These bubbles weaken the structure significantly—instead of solid, dense material, you have material full of tiny voids that fail under stress [48]. Third, if you dry your material one day and the air is humid, your TPU will reabsorb moisture [28]. This creates batch-to-batch inconsistency. One print might work perfectly, the next one might fail, and you'll struggle to understand why [49].

3.1.2 TPU Drying Specifications

The specification is straightforward but non-negotiable: TPU pellets must be dried to ≤0.05% moisture content at temperatures between 80–110°C for 1–3 hours before extrusion [10], [28]. This isn't an optional guideline or a best practice suggestion—it's a hard requirement [28].

3.1.3 TPU Drying Process Steps

The drying process involves measuring the moisture content if possible using Karl Fischer titration or time-domain reflectometry [28], setting up a commercial desiccant dryer set to 90°C (optimal for both TPU 95A and 93A) [28] with fresh desiccant (silica gel or molecular sieve) [28] for 2–3 hours minimum [28]. Once dried, pellets should be put in a sealed container with desiccant inside [28]. Don't let them sit in humid air—they'll reabsorb moisture [49]. Just because you dried something this morning doesn't mean it's still dry when you go to print in the afternoon [28]. In humid climates especially, re-dry if storage has exceeded 24 hours in ambient humidity [28]. Many experienced TPU users have gone through the frustration of mysterious printing failures that magically resolved once they started implementing proper moisture management [28]. The material works fine if it's dry. It consistently fails if it's wet. It's that simple [28].

3.1.4 PLA Conditioning Requirements

PLA is less hygroscopic than TPU, meaning it doesn't absorb as much moisture, so the problem isn't as severe [50]. But proper conditioning still measurably improves results [50]. Drying PLA at 80°C for 2–4 hours before printing improves tensile strength and surface finish [50]. It's not absolutely required like it is for TPU, but it's a relatively simple step that yields noticeable improvements, so most practitioners do it [50].

3.2 Equipment Requirements and Hardware Modifications

3.2.1 Standard PLA Hardware Setup

For PLA, standard FDM equipment works reasonably well [51]. A 0.4 mm brass nozzle, standard heating barrel, typical print bed temperature of 60°C—these are fine [51]. Modern FDM systems designed for PLA have sufficient thermal control to get good results [51]. Higher-end systems with better temperature regulation (±2°C instead of ±5°C) produce slightly superior results, but standard equipment can definitely work [51].

3.2.2 TPU Equipment Challenges

Here's where many projects go wrong: people think they can just load TPU into their PLA printer and get results [10]. This doesn't work [10]. TPU has physical properties that create specific challenges [27]: it expands a lot when heated, more than PLA does [27]; it has a tendency to stick and clog the nozzle [27]; flow becomes unstable and can overflow suddenly [27].

3.2.3 PTFE-Coated Nozzles Requirements

To address these challenges, you need hardware modifications that aren't optional—they're essential [10], [27]. PTFE-Coated Nozzles are critical: standard brass nozzles don't work well with TPU [27]. The material sticks to brass [27]. PTFE (Teflon) coating dramatically reduces friction and prevents sticking [27]. This is the single most important hardware change. Many TPU printing failures trace directly to inadequate nozzle coatings [10]. If you're using a brass nozzle for TPU, you're setting yourself up for failure [27].

3.2.4 Extended Barrel Modifications

Extended Barrels are also necessary: the heating barrel needs to be 1.2–1.5 times longer than standard PLA/ABS configurations [10]. This longer barrel accomplishes several things: it reduces friction by allowing material to move more slowly through the heated chamber [10]; it suppresses overflow and pressure buildup [10]; it allows material to equilibrate thermally without excessive heating [10]; and it reduces shear stress that would degrade the material [52].

3.2.5 Temperature Control Precision

Precise Temperature Control is required: TPU requires ±2°C temperature stability (not the ±5°C that's acceptable for PLA) [10]. This means higher-quality thermistors and more careful PID controller tuning [53].

3.2.6 Build Platform Adjustments

Build Platform Adjustments include the following considerations: the bed temperature should be slightly lower (50°C vs. 60°C for PLA) to prevent initial adhesion from being excessively strong [10]. The bed material matters too—textured PEI or specialized elastomer-compatible surfaces work better than standard glass [51]. And bed leveling must be very precise (±0.05 mm) [27].

3.2.7 Critical Nature of Hardware Modifications

These aren't minor tweaks or optimizations. They're essential modifications without which TPU printing either won't work or produces consistently inferior parts [10], [27].

3.3 Process Parameter Optimization

3.3.1 PLA Layer Thickness as Critical Variable

For PLA, research consistently shows that one factor matters most: layer thickness [11]. This isn't just a minor effect—it's often the most significant manufacturing parameter affecting the final result [11]. When you print with thick layers (0.2 mm), you have fewer layer interfaces (the boundaries between successive layers) [11]. These interfaces are weak points where the material is prone to fail [11]. Fewer interfaces means higher overall strength. You get roughly 30–50% more tensile and compressive strength with 0.2 mm layers compared to 0.1 mm layers [11].

3.3.2 Strength-Resolution Tradeoff

But there's a tradeoff: thicker layers reduce geometric resolution [11]. If you're printing something with intricate internal features, you need thin layers to capture those details [11]. So you have to decide: do you prioritize strength or detail [11]? For medical devices with complex internal features, you might accept reduced strength and use 0.1–0.15 mm layers [12]. For load-bearing aerospace components, you'd use 0.2 mm layers [47]. For a balance in soft robotic actuators, 0.15 mm is a reasonable compromise [13].

3.3.3 Recommended PLA Parameters

The recommended PLA parameters include layer thickness of 0.2 mm for strength; 0.1 mm for detail [11], nozzle temperature of 200–210°C (200°C for thin walls, 210°C for thicker structures) [54], print speed of 50–80 mm/s [55], bed temperature of 60°C [55], retraction distance of 4–5 mm [56], and retraction speed of 40 mm/s [56].

3.3.4 TPU 95A Extrusion Speed Control

This is where TPU printing gets genuinely demanding [10]. The optimal extrusion speed range for TPU 95A is remarkably narrow: 990–1045 mm/min [10]. That's only a 55 mm/min window. This represents one of the tightest process windows in all of additive manufacturing [57].

3.3.5 Low Speed Degradation Mechanisms

Why is this so constrained [10]? Because two opposite problems exist: If you push material too slowly (below 990 mm/min), material stays in the hot barrel too long [58]. It cools prematurely, creating flow inconsistencies [58]. Prolonged residence time in heat causes thermal degradation [58]. Material properties degrade [58].

3.3.6 High Speed Degradation Mechanisms

If you push material too fast (above 1045 mm/min), excessive shear stress develops as material gets forced through the nozzle [10]. This frictional heating adds 5–10°C to the nominal barrel temperature, pushing the material close to its melting point [10]. Polymer chains break through mechanical shearing (chain scission) [59]. You can lose 25–30% of the material's elongation at break and 20–25% of tensile strength [10]. Shape recovery reliability drops from 100% to 85–90% [10].

3.3.7 Process Control Requirements for TPU

This explains why TPU printing requires such careful process control and specialized hardware [10]. You can't just "turn up the speed" like you might with PLA [10]. You're right in the middle of a narrow band, and deviations in either direction cause problems [10].

3.3.8 TPU 95A Parameter Table

Table 1. Type Sizes for Camera-Ready Papers

Sr. No.	Parameter	Value	Why this Matters	
1	Nozzle temperature	210°C	Optimal material flow without degradation	[43]
2	Barrel temperature	190°C	Lower than nozzle to prevent degradation in barrel	[43]
3	Extrusion speed	990–1045 mm/min	Narrow window to prevent both low and high speed problems	[10]
4	Layer thickness	0.2–0.3 mm	Thicker than PLA to reduce interface count	[10]
5	Bed temperature	50°C	Slightly lower to prevent excessive adhesion stress	[27]
6	Nozzle diameter	0.4 mm	Standard diameter balancing flow rate and resolution	[51]

3.3.9 TPU 93A Parameter Adjustments

Different TPU grades require slightly different parameters [8], [46]. For TPU 93A (softer), use 205°C nozzle temperature (5°C lower due to its 129.2°C melting point) [8], and a slightly tighter speed window (980–1040 mm/min) [8].

3.3.10 NinjaFlex Parameter Adjustments

For NinjaFlex, use 200°C nozzle temperature (10°C lower) [46], and the tightest speed window (960–1010 mm/min) [46].

3.4 Build Orientation Strategy

3.4.1 Importance of Build Orientation

How you orient your part during printing has enormous practical consequences, something that often gets underestimated [30], [61]. When you print with layers building horizontally (perpendicular to the print bed, called XY printing) [30], the material's fiber-like structure runs parallel to the direction of applied loads [30]. This gives you maximum strength—typically 30–50% higher tensile strength than vertical printing [30].

3.4.2 Horizontal vs. Vertical Printing Effects

When you print with layers oriented vertically (called ZX printing) [30], loads get applied parallel to the layer interfaces [30]. These interfaces are the weak points in the material [30]. You get significantly lower strength and increased vulnerability to delamination (layers separating from each other) [62].

3.4.3 Anisotropy Effects on Shape Recovery

For 4D printing, this anisotropy (directional property difference) doesn't just affect strength—it affects shape recovery itself [63]. Structures printed horizontally recover their programmed shapes more reliably and faster than those printed vertically [63].

3.4.4 Smart Design Strategies

Smart design explicitly leverages this by orienting load-bearing features horizontally for maximum strength [30], orienting transformation directions to align with superior recovery properties [63], and placing crease lines where anisotropy helps create sharp, predictable folding [30].

3.4.5 Consequences of Inadequate Orientation

Inadequate attention to orientation can reduce functional lifespan from 1,000+ cycles to fewer than 100 cycles in soft robotic applications [64]. It's not a minor detail [30].

4. Results and Analysis

4.1 Thermal Characterization of Materials

4.1.1 PLA Thermal Behavior Overview

The thermal properties of PLA are well-established and highly predictable, a characteristic that proves particularly valuable when engineering reliable, performance-consistent components [5], [39]. Below its glass transition temperature of 57°C, PLA remains rigid and faithfully retains whatever shape it was programmed into during fabrication [5]. As the material is heated into the 57–177°C range, it transitions into a softened, deformable state where external forces or stored mechanical energy can reshape it [5], [65]. Once temperatures exceed 177°C, PLA enters a viscous liquid phase, rendering it unsuitable for structural purposes [5]. This clear, stepwise thermal behavior makes PLA an exceptionally tractable material for shape memory engineering applications where precise and repeatable thermal triggers are required.

4.1.2 Medical Application Advantages

From the standpoint of medical device design, PLA's thermal profile is nearly ideal [12]. The human body maintains a core temperature of approximately 37°C—well below PLA's glass transition threshold of 57°C—which means an implanted PLA device will remain dimensionally stable under physiological conditions and reliably hold its programmed geometry [12]. When controlled thermal activation is desired, applying localized heat to raise the material slightly above 57°C initiates the glass transition, enabling the device to transform toward its programmed target shape [12]. This narrow thermal operating window between body temperature and the activation threshold provides clinicians and engineers with a meaningful safety margin, allowing deliberate shape transformation without inadvertent activation in the body's normal thermal environment [12].

4.1.3 Rigid Nature and Folding Benefits

PLA's inherent rigidity—characterized by an elongation at break of only 1.4%—means the material does not deform indiscriminately under load [5]. Rather than exhibiting random plastic deformation, PLA folds predictably along engineered crease lines, producing clean and controlled structural transitions [38]. This behavior is not a limitation but a deliberate design advantage: for medical devices requiring precise geometrical transformations, the ability to engineer specific fold patterns and predict their outcomes with confidence is essential to reliable device function [38].

4.1.4 Thermal Property Variations with FDM Parameters and Shape Recovery Variability

The specific thermal properties achieved in a finished PLA print are not fixed constants but vary measurably with the process parameters used during fabrication [29], [66]. Printing with 0.2 mm layers under slower cooling conditions tends to produce glass transition temperatures in the 57–59°C range, as the extended cooling time permits a greater degree of polymer crystallization [29]. In contrast, 0.1 mm layers printed under faster cooling conditions yield lower glass transition temperatures of approximately 55–56°C, since the rapid quench suppresses crystallinity [66]. Variations in print speed introduce additional thermal variability, causing T_g to shift by roughly ±2°C depending on the overall thermal history experienced by the material during deposition [29]. This process sensitivity directly explains why shape recovery rates can vary by 2–3% between nominally identical prints. While consistent print speed and layer thickness can substantially reduce this variability, complete elimination remains impractical, underscoring the need for tight process control in precision applications [29].

4.1.5 TPU 95A Temperature Constraints and Medical Application Constraints

TPU 95A exhibits a critical phase transition at 56°C that imposes a hard operational limit on any application involving this material [10], [43]. Unlike PLA's more gradual glass transition, this change in TPU 95A is an abrupt phase transformation—and crossing the 56°C threshold even once causes permanent, irreversible material degradation [43]. The consequences are substantial: the elastic modulus drops by 20–30%, shape memory capability is lost entirely, and no amount of subsequent cooling restores the material to its original properties [43]. For medical applications where body temperature sits at 37°C, this creates a meaningful but manageable design constraint [12]. Thermal activation to trigger shape transformation is entirely feasible, provided temperatures are carefully controlled to remain below the 56°C degradation threshold. A single exceedance—whether from processing conditions, sterilization procedures, or inadequate thermal control—permanently compromises the device's functional properties [43].

4.1.6 TPU 93A Extreme Temperature Operation

TPU 93A's glass transition temperature of -47°C represents a genuinely remarkable material property [8]. While TPU 95A would suffer mechanical compromise in cold environments, TPU 93A retains full flexibility even under arctic conditions, opening application possibilities inaccessible to most conventional elastomers [43], [44]. Practically, this means TPU 93A-based structures can function reliably in underwater robotics operating in deep-ocean environments at approximately 4°C, in arctic exploration platforms subjected to temperatures as low as -40°C, and in aerospace systems exposed to high-altitude thermal conditions approaching -55°C [44], [45]. These extreme-temperature capabilities position TPU 93A as a uniquely suited material for next-generation robotic and exploration systems where thermal resilience across wide operating ranges is a fundamental design requirement.

4.2 Process Parameter Impact on Performance

4.2.1 Layer Thickness, Mechanical Properties, and Honeycomb Structures

Research data establishes clear and quantifiable relationships between layer thickness and the mechanical performance of FDM-printed SMP components [11], [67]. At a layer thickness of 0.2 mm, printed samples exhibit tensile strength of approximately 45 MPa and compressive strength of approximately 70 MPa, with initial shape recovery rates of 98–100% and 5-cycle recovery rates of 92–95% [11]. Reducing layer thickness to 0.1 mm results in a significant decline across all performance metrics: tensile strength drops to approximately 30 MPa (a 33% reduction), compressive strength falls to approximately 48 MPa (a 31% reduction), and recovery performance diminishes to 95–98% initially and 85–88% after five cycles [11]. These are measured results from physical testing, not approximations, and the performance differential is both real and practically significant [11]. For honeycomb structures commonly employed in 4D actuators, layer thickness frequently emerges as the dominant determinant of compression strength [68]. This relationship is non-linear—doubling layer thickness does not proportionally double strength, but the improvement is nonetheless substantial and must be accounted for in structural design [11].

4.2.2 Build Orientation Effects on Strength and 4D Structure Design

The influence of build orientation on mechanical performance represents one of the most consequential findings in FDM 4D printing research, with tensile strength varying by 30–50% depending on print direction [30], [61]. Horizontal (XY) printing yields tensile strengths of 45 MPa, 90% shape recovery in 3–5 seconds, and recovery reliability of 96–98% [30], [63]. Vertical (ZX) printing, by contrast, produces tensile strengths of only 28–32 MPa—30–50% lower—along with slower 90% recovery times of 4–6 seconds and reduced reliability of 92–94% [30], [63]. For 4D structures designed to fold or transform in specific, controlled ways, this anisotropy is a critical design variable rather than a peripheral consideration [30]. A structure engineered to fold along a defined axis may perform reliably when printed horizontally but exhibit inconsistent or failed recovery when printed vertically, underscoring the need for build orientation to be an intentional design decision made in conjunction with performance targets [63].

4.2.3 TPU Extrusion Speed Performance Data

Table 2 presents empirical data from actual printing trials illustrating the performance consequences of varying TPU extrusion speed across a range of operating conditions [10], [57]:

Table 2. TPU 95A Extrusion Speed vs. Material Performance [10]

Sr. No	Speed (mm/min)	Tensile Strength	Elongation	Shape Recovery (%)	Result	Ref.
1	960 mm/min	38 MPa	550%	94	Below optimal window	[10]
2	990 mm/min	40 MPa	600%	100	Minimum optimal	[10]
3	1010 mm/min	40 MPa	600%	100	Center of window	[10]
4	1045 mm/min	40 MPa	600%	100	Maximum optimal	[10]
5	1080 mm/min	32 MPa	420%	85	Shear degradation begins	[10]
6	1120 mm/min	28 MPa	340%	70	Severe degradation	[10]

4.2.4 Speed Window Analysis

The data in Table 2 illustrates why the optimal extrusion speed window for TPU is so narrow and why operating outside it carries serious performance consequences [10]. Within the range of 990–1045 mm/min, consistent and high-quality results are reliably achieved, with tensile strength of 40 MPa, elongation of 600%, and full 100% shape recovery [10]. Below this window, at 960 mm/min, performance already begins to deteriorate. Above it, shear-induced degradation sets in rapidly: at 1080 mm/min, tensile strength drops to 32 MPa and shape recovery falls to 85%, and at 1120 mm/min the material is severely degraded, with tensile strength of 28 MPa and recovery reduced to just 70% [10]. This narrow window demands precise, well-calibrated speed control in any production environment.

4.3 Cyclic Degradation Characteristics

4.3.1 Initial Recovery Performance and Cyclic Degradation Pattern

Upon initial activation, 4D structures generally demonstrate strong shape recovery performance across material types [69], [70]. Well-designed PLA structures achieve 90–98% initial recovery, with optimized geometries reaching the upper end of that range at 96–98% [70]. TPU structures perform comparably, with initial recovery rates of 95–100%, as do SLA-printed reference structures [70], [71]. While these initial results affirm that the fundamental shape memory mechanism functions as intended, sustained cyclic performance tells a more nuanced story. When structures are subjected to repeated transformation-and-recovery cycles, performance degrades progressively—a pattern that has important implications for any application requiring multiple actuations over the device's service life [15], [16].

4.3.2 PLA Honeycomb Cyclic Recovery Data

Table 3 presents measured recovery rates for PLA honeycomb structures undergoing repeated actuation cycles [15], [16]:

Table 3. PLA Honeycomb Cyclic Recovery Performance [15], [16]

Cycle	Recovery Rate (%)	Drop from Cycle 1	Ref.
1	98%	Baseline	[15]
2	96%	2% drop	[15]
3	93%	5% drop	[15]
4	89%	9% drop	[15]
5	87%	11% drop	[15]

4.3.3 Significance of Cyclic Degradation and Micro-Fracture Accumulation

An 11% absolute reduction in shape recovery performance across just five cycles is a materially significant finding [15]. If this degradation trajectory continues, the structure would fall below acceptable performance thresholds within 10–15 cycles—a severe limitation for any application requiring sustained cyclic operation [15]. The underlying mechanism is micro-fracture accumulation: each transformation cycle introduces tiny internal cracks and localized material damage that, while individually invisible, accumulate progressively over repeated loadings [72]. The cumulative effect of these micro-fractures is a reduction in material stiffness, a diminished capacity for shape recovery, and an increased susceptibility to catastrophic failure as cycle count grows [72], [73]. Understanding this failure mode is essential to selecting appropriate applications for FDM 4D-printed components.

4.3.4 Application-Specific Cyclic Performance Implications

The practical significance of cyclic degradation is highly context-dependent and varies considerably across application domains. For medical devices intended for single deployment—such as a stent that expands once and remains permanently in its deployed configuration—cyclic degradation presents no functional concern, as the material is never required to recover [74]. Soft robotic actuators present a more demanding scenario: a gripper mechanism required to cycle through grasping and releasing operations hundreds of times will begin exhibiting unacceptable performance after as few as 20 cycles, given current material limitations [13], [75]. Aerospace morphing structures face the most severe constraints—if wing panels must adaptively reconfigure thousands of times across a flight season, current FDM materials are simply not adequate for sustained, high-cycle service [47]. Similarly, reversible deployment systems sacrifice 1–2% of performance with each deployment-recovery cycle, leaving them with a limited number of reliable activations before functional failure [74].

4.3.5 Build Orientation and Cyclic Performance

The anisotropic character of FDM printing affects not only initial mechanical performance but also how gracefully structures tolerate repeated actuation cycles [63], [76]. Horizontally (XY) printed structures achieve 90% recovery in 3–5 seconds with reliability of 96–98%, and they exhibit superior cyclic stability—performance degrades slowly and predictably over successive cycles [63]. Vertically (ZX) printed structures, while acceptable in initial single-cycle performance at 92–94% reliability and 90% recovery in 4–6 seconds, undergo faster cyclic degradation [63]. This performance difference is attributable to differences in internal stress distribution: horizontal printing produces interlayer bond geometries that distribute cyclic stresses more favorably, thereby slowing the rate of micro-fracture nucleation and accumulation compared to the inter-layer stress concentrations inherent in vertical printing [63].

5. Discussion

5.1 Material Selection Framework

5.1.1 Importance of Material Selection

Material selection is one of the most consequential decisions in the development of any FDM 4D-printed device or structure [77], [78]. Selecting an inappropriate material for a given application will result in functional failure regardless of how meticulously all other process parameters are optimized. The thermal, mechanical, and cyclic properties of available SMP materials differ substantially, and matching material characteristics to application requirements is a prerequisite for reliable performance outcomes.

5.1.2 When to Use PLA and Typical PLA Applications

PLA is the material of choice when the final deployed structure must be dimensionally rigid, when biodegradability is advantageous—as in temporary medical implants or resorbable scaffolds—and when sharp, well-defined transformation behavior is required [5], [28]. It is well-suited to applications with moderate operating temperatures in the 37–100°C range, where single-use or very low-cycle deployment is acceptable, and where biocompatibility is a regulatory or clinical requirement [5], [12], [15]. Cost is also a favorable consideration at $15–25/kg [79]. Practical applications that exemplify these characteristics include personalized medical stents, controlled drug delivery systems, tissue engineering scaffolds, single-deployment aerospace structural components, and orthodontic devices [12], [28], [37], [47].

5.1.3 When to Use TPU 95A and Typical Applications

TPU 95A is the appropriate choice when the application demands flexible, compliant structures capable of generating substantial actuation forces, particularly in soft robotic contexts requiring actuators that interact safely with delicate surfaces or biological tissues [41]. It is suited to applications where limited cyclic operation—up to approximately 20 cycles before meaningful performance degradation—is acceptable, where operating temperatures will remain safely below the 56°C degradation threshold, and where moderate flexibility combined with meaningful structural integrity is required [15], [41], [43]. Established applications for TPU 95A include soft robotic grippers, prosthetic joint components, minimally invasive surgical manipulators, flexible medical catheters, and underwater robotic systems operating at moderate depths [13], [37], [45], [80].

5.1.4 When to Use TPU 93A and Typical Applications

TPU 93A is selected when applications impose extreme cold-temperature operational requirements at -40°C and below, when maximum structural compliance is a primary design objective, or when the operating environment involves deep underwater deployment or sustained exposure to sub-zero conditions [8], [44]. It is particularly valuable where conventional elastomers would become brittle and where ultra-compliant behavior must be maintained throughout the full operational temperature range [8]. Representative applications include arctic exploration robotic platforms, deep-sea autonomous systems, and any extreme-temperature application where maintaining flexibility across a wide thermal range is non-negotiable [44], [45].

5.2 Interconnected Success Factors

5.2.1 Material Science, Conditioning, Hardware, and Process Parameter Control

Achieving reliable performance in FDM 4D printing requires simultaneous success across multiple, deeply interconnected domains rather than isolated optimization of individual parameters [17]. At the foundation, material science demands the selection of a polymer with thermal properties and shape memory characteristics precisely matched to the intended application—there is no universal SMP material that performs well across all contexts, and attempting to substitute one material type for another invariably produces suboptimal outcomes [5], [7], [10]. Adequate material conditioning is equally non-negotiable: for hygroscopic materials like TPU, rigorous moisture management—including controlled drying, proper storage, and pre-print verification—is essential and prevents the most prevalent category of processing failures [28]. Hardware must similarly be matched to the material being processed; PLA and TPU require fundamentally different equipment configurations, and operating with mismatched hardware produces consistent failure regardless of how well other parameters are controlled [10], [27], [51]. Finally, process parameters must be maintained within precisely defined tolerances—temperature control to within ±2°C for TPU, and tightly regulated print speed—with every parameter documented and reproduced consistently across production runs [10], [43], [60].

5.2.2 Design Integration, Build Orientation, Quality Assurance, and Interconnected Nature

Beyond material and equipment considerations, effective 4D printing requires that design and process decisions be fully integrated from the outset [25], [35]. Mathematical modeling and computational analysis are indispensable tools for engineering the specific transformations a device must execute; assumptions about deformation behavior cannot be reliably made without analytical validation [25]. Build orientation must be treated as a primary design variable, strategically chosen to leverage the inherent anisotropy of FDM and thereby achieve 30–50% performance improvements in the structural directions that matter most for the intended application [30]. Comprehensive quality assurance—including systematic cyclic recovery testing—is required to establish the bounds of reliable performance and confirm that parts will meet their service requirements throughout their intended operational life [70]. Critically, none of these factors can be optimized in isolation. Excellent material selection cannot compensate for incorrect hardware; perfect equipment cannot overcome inadequate conditioning; and appropriate conditioning and equipment are insufficient without design decisions that account for build orientation and process window constraints [10], [17], [28], [30].

5.3 The Biggest Current Limitation: Cyclic Degradation

5.3.1 Cyclic Performance Limitations

The most significant constraint limiting the broader deployment of FDM 4D printing is the inability of current SMP materials to sustain hundreds or thousands of actuation cycles without meaningful performance loss [15], [16]. For applications involving single or very limited transformations—such as medical devices that deploy once and remain fixed—this limitation poses no practical barrier [12], [74]. However, for applications such as aerospace morphing structures that must adapt thousands of times across a service period, current FDM materials fall well short of the cyclic durability required [47].

5.3.2 Active Research Directions and Timeline

Active research efforts are underway to address cyclic fatigue limitations through several distinct approaches, including the development of SMP formulations with enhanced fatigue resistance, the use of fiber reinforcement to interrupt micro-fracture propagation pathways, the synthesis of novel polymer chemistries specifically tailored for high-cycle loading, and the incorporation of nanoparticle reinforcement agents such as graphene or carbon nanotubes to strengthen the polymer matrix. While these approaches show meaningful scientific promise, commercially available and fatigue-resistant SMP materials suitable for high-cycle FDM 4D printing remain several years from broad market availability.

5.4 Standardization and Regulatory Gaps

5.4.1 Lack of Standardization, Importance, Required Work, and Timeline

A significant barrier to the widespread adoption of 4D printing in regulated industries is the absence of universally accepted testing methodologies, design guidelines, and quality standards. This gap is particularly consequential in aerospace and medical device development, where regulatory approval depends on validated, reproducible characterization protocols that do not yet exist for 4D-printed SMP components. Before the technology can transition from specialty research applications to mainstream manufacturing, standardization must be established across a comprehensive set of domains: testing methodologies for material thermal and mechanical properties, standardized shape recovery measurement protocols, cyclic durability testing frameworks, application-specific design guidelines, quality assurance processes, and regulatory approval pathways for safety-critical uses. While standardization efforts are actively underway in various research and standards bodies, completion of this work will realistically require several additional years, with timelines varying depending on the specific application domain and regulatory jurisdiction.

6. Conclusion & Recommendations

6.1 Current State and Key Findings

6.1.1 Evolution from Theory to Practice and Fundamental Challenges Solved

FDM-based 4D printing has undergone a substantial evolution from theoretical concept to practical manufacturing capability [1], [5], [17]. The underlying materials science is well understood, shape memory mechanisms have been rigorously characterized, and real-world applications are operational today [31], [32]. Medical devices fabricated using these techniques are being implanted in patients, soft robotic structures are advancing from proof-of-concept to functional prototypes, and research projects across multiple domains have demonstrated credible engineering applications [12], [13], [47]. The fundamental scientific challenges have been resolved [1], [5]: the mechanisms governing shape memory behavior are established [31], [32], the methods for encoding programmable shape change through FDM processing are known [35], and the material and process parameters that produce reliable outcomes have been systematically characterized [10], [11].

6.1.2 Material-Specific Optimization and Narrow Process Windows

A consistent conclusion that emerges from the technical evidence is that material-specific optimization is non-negotiable [10], [43]. PLA and TPU behave in fundamentally different ways under thermal and mechanical loading and require entirely distinct processing approaches; no universal FDM 4D printing protocol exists that performs well across both material classes [10], [43]. Compounding this, the process windows for certain materials—particularly TPU—are exceptionally narrow by manufacturing standards [10], [57]. The optimal TPU extrusion speed window of 990–1045 mm/min represents one of the tightest process tolerances in common manufacturing practice, and any deviation from this range produces measurable performance degradation that cannot be recovered through downstream adjustments [10], [57].

6.1.3 Cyclic Degradation, Build Orientation, and Hardware Requirements

Cyclic degradation remains the defining limitation for applications requiring sustained, repeated actuation [15], [16]. A drop from 98% recovery at cycle 1 to 87% by cycle 5 illustrates that current FDM SMP materials are well-suited to single-use or very low-cycle deployments but are inadequate for high-cycle operational demands without further material development [15], [16]. Build orientation equally demands recognition as a primary performance determinant: the 30–50% difference in tensile strength between horizontal and vertical printing has direct consequences for structural integrity and recovery reliability that must be addressed explicitly in design [30], [61]. For TPU, hardware requirements are similarly non-negotiable—PTFE-coated nozzles and 1.2–1.5× extended barrel configurations are not optional upgrades but essential infrastructure for reliable, repeatable TPU printing [10], [27].

6.2 Implementation Roadmap

6.2.1 Phase 1: Application Definition

A structured phased approach is recommended for practitioners considering the adoption of 4D printing [17]. The first phase requires precise application definition: identifying exactly what the device or structure must accomplish, determining the stimulus type that will trigger transformation (temperature, moisture, light, or other), establishing the required number of actuation cycles over the component's service life, and defining acceptable performance tolerances [1], [17], [74]. This clarity is prerequisite to all subsequent decisions.

6.2.2 Phase 2: Material and Equipment Selection

Material and equipment selection must be driven directly by the application requirements established in Phase 1 [5], [7], [51]. The appropriate SMP material should be identified based on thermal activation range, cyclic durability needs, mechanical requirements, and any biocompatibility or regulatory constraints. Compatible printing hardware must then be acquired, including material-specific nozzle configurations and barrel geometries [27], [51], proper material conditioning procedures must be established and validated [28], and equipment performance should be confirmed through systematic test prints before production commitments are made [51].

6.2.3 Phase 3: Process Development

Process development involves optimizing all printing parameters within the established material-specific windows [10], [43], physically testing the mechanical properties of printed samples to confirm performance [11], validating design assumptions through systematic prototyping [35], and establishing quality control procedures that can be consistently executed across production runs [70].

6.2.4 Phase 4: Application Design and Prototyping

Part design must fully exploit the specific performance characteristics of the chosen material, optimizing geometry for build orientation, fold mechanics, and recovery pathway [5], [7]. Computational analysis should be employed to predict transformation behavior prior to physical fabrication [25], followed by iterative prototype-test-refine cycles [25]. Every parameter, procedure, and design decision should be meticulously documented throughout this phase to support reproducibility and regulatory compliance [17].

6.2.5 Phase 5: Validation and Deployment

The final phase encompasses comprehensive performance validation testing, establishment of formal quality assurance protocols that define acceptance criteria and testing procedures [70], thorough documentation of all fabrication processes and design rationale [17], and deployment accompanied by structured performance monitoring to detect any drift from validated performance baselines over the component's service life [17].

6.3 Final Perspective

6.3.1 Nature of Innovation and Engineering Work Required

4D printing represents a substantive and durable technological innovation rather than a transient research interest [1], [17]. It is transitioning from an intriguing laboratory demonstration to a practical manufacturing capability, supported by well-understood science, proven materials, and operational real-world applications [5], [12], [13]. What the field requires now is not further fundamental scientific discovery but deliberate engineering work: the development of standardization frameworks, cost reduction through process maturation and scale [26], broader industrial adoption, and refinement of the implementation methodologies that have been established through research [17]. This constitutes the primary agenda for the technology over the coming 5–10 years as it moves from research-led specialty applications into broader industrial use [17].

6.3.2 Practitioner Readiness and The Next Manufacturing Revolution

For practitioners actively evaluating whether to adopt 4D printing for a specific application, the technology is functionally ready and has been demonstrated to work reliably when deployed appropriately [1], [5], [17]. However, success is contingent on recognizing that this is not a general-purpose manufacturing technology. It is material-specific, process-parameter-sensitive, and highly application-dependent [10], [43], [17]. When applied to use cases where it genuinely offers a performance advantage—self-deploying medical devices, compliant actuators, extreme-environment robotic systems—4D printing delivers capabilities that conventional manufacturing cannot match [12], [13]. When applied to scenarios where it offers no meaningful benefit, or where its constraints are not accounted for, failure is predictable [10]. Looking further ahead, the next frontier of manufacturing advancement will not be defined by incremental gains in printing speed or cost reduction alone, but by the development of materials capable of intelligently evolving their structure in response to environmental stimuli [1]. 4D printing is precisely where that transformation is taking place today [1], [17].

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