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THE EFFECTS OF PRINTING PARAMETERS ON SHAPE TRANSFORMATION CAPABILITY OF 3D PRINTED STRUCTURES OF SMART MATERIAL

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Abstract: This study investigates the effects of 3D printing parameters on the shape transformation capabilities of structures fabricated from a composite of 80% PCTG, PET, PTMG, and 20% additives with shape memory properties. Different values of printing speed, infill density, and water temperature after printing have significant effects on the structures of PCTG-based with SMPs that influence the shape memory behaviour. In order to improve the effectiveness and precision of shape recovery under heat stimuli, the research uses the shape memory polymer (SMP) principle to optimize three important parameters, which are printing speed, infill density, and water temperature after printing. Samples were created using fused deposition modeling (FDM) technology across 27 experiments, and their recovery functionality time and thermal responsiveness were then assessed. The project employs Taguchi analysis to analyse the results by using ANOVA method. The results showed that the most important factor influencing shape recovery was the water temperature after printing, which was followed by printing speed and infill density. While lower infill densities improved flexibility and shortened recovery time, higher temperatures led to faster recovery. On the other hand, slower printing speeds lengthened the print time but enhanced interlayer stability and adhesion. A printing speed of 40 mm/s, an infill density of 30%, and a post-printing water temperature of 100°C were found to be the optimal parameter combination, resulting in the quickest recovery time of 7.27 seconds. This study provides important insights for developing 4D printing technologies by highlighting the crucial interaction between printing parameters and external factors in determining the performance of 3D-printed SMP structures. This study fills in gaps in the literature, laying the groundwork for the reliable design and production of smart materials with revolutionary potential.
Keywords: shape memory polymers; 3D printing; PCTG; shape recovery; printing speed; infill density; material structures; water temperature

1. INTRODUCTION

With the growing interest in smart materials and their applications in adaptive structures, this study investigates 3D printing, where heat acts as a stimulus to trigger shape changes in materials composed of PCTG, PET, and PTMG. In order to improve shape recovery, it seeks to optimize three important parameters: printing speed (40, 70, and 100 mm/s), infill density (30, 60%, and 90%), and water temperature (60, 80, and 100 °C) after printing. The mechanical, thermal, and shape transformation performance of printed specimens was assessed through experiments with different parameters, with an emphasis on how well the specimens returned to their original shape. The project utilizes statistical tools like Minitab software to create Taguchi analysis and ANOVA, which aids to interpret the functionality time taken to activate the shape memory behavior of the printed PCTG-based

SMP material. The use of SEM analysis provides good values in justifying the effects of printing speed, infill density, and water temperature after printing on the material's structures. The slight difference in structures within the printed object leads to significant changes in the shape memory characteristics. To address these challenges, this study sets out the following objectives:

i. To evaluate the effects of printing speed, infill density, and water temperature after printing on printed structures of smart materials by using SEM analysis.

ii. To determine optimal parameters for printing and heating the printed part made from a composition of PCTG, PET, PTMG, and other additives on shape recovery by using Taguchi analysis.

iii. To evaluate the recovery functionality time of the sample when applying heat stimuli by using a hot water bath.

Digital fabrication or additive manufacturing is an advanced manufacturing technique that creates physical objects from digital design to gradually construct products [1]. Using three-dimensional (3D) model data, additive manufacturing (AM) processes such as 3D printing can be used to create a variety of complex geometries and structures [2]. 3D printing is a customized process that can produce intricate shapes appropriate to the desire and requirement of the user [3]. Compared to traditional machining, 3D printing allows simulation. This simulation helps to improve understanding and visualize the complex thermo-chemical occurrence while manufacturing [4]. This provides a high-quality and high-accuracy production. Four-dimensional (4D) printing enhances traditional 3D printing by adding the dimension of time, enabling objects to transform their shape or properties in response to external stimuli like heat or light [5]. Unlike static 3D-printed parts, 4D-printed structures incorporate dynamic behaviors, offering flexibility, efficiency, and innovative functionality. This technology, particularly with PCTG-based SMPs, transforms the design and operation of smart materials, enabling adaptive and responsive applications.

Polylactic acid (PLA) is a widely used, eco-friendly polymer in FDM due to its biocompatibility and thermoplastic properties. It demonstrates shape memory behavior through polymer chain entanglements, which allow it to return to its original shape after being temporarily deformed when heated to its transition temperature [6]. The thermoplastic polyester known as polyethylene terephthalate (PET) is incredibly resilient to chemicals, thermally stable, and inexpensive to manufacture. Even though PET is rarely used in FDM, PET's mechanical qualities are adequate for producing lightweight 3D models for analysis and visualization [7]. PCTG, a polyester similar to PETG, is a superior alternative due to its higher impact strength, greater durability, broader printing temperature range, and enhanced chemical resistance, making it more versatile and robust for various applications [8]. PTMG has unique mechanical and thermal properties in creating shape memory and self-healing. This polymer exhibits good elasticity, making it suitable for applications that require repeated deformation and recovery [9]. With high thermal stability, it enables effective functionality under temperature variation.

2. MATERIALS AND METHODS

2.1. Sample Fabrication

The design was created using SOLIDWORKS software due to its suitability for specifying materials, dimensions, and ease of use. The design, a rectangular shape with dimensions 80 x 20 x 3 mm, was converted into an .stl file and sliced into thin layers using CURA Slicer to generate printer-compatible code. Then, the samples were fabricated using a Creality Ender-3 V3 SE 3D Printer. The design was tested for shape transformation under specific water heat stimuli. Figure 1 shows the sample design with a rectangular shape used in the study.

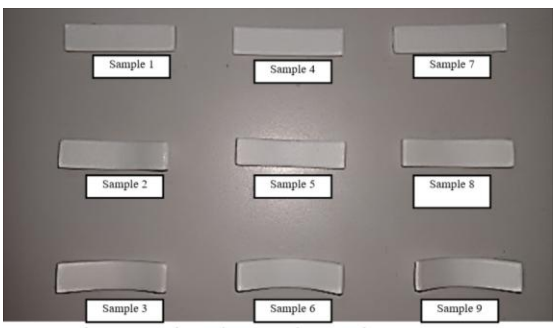

Fig. 1. Printed Sample Design

Fig. 2. Techne TE-10D Tempunit Water Bath

The heating process utilized a Techne TE-10D Tempunit hot water bath, chosen for its precise temperature control, suitable for moderate transition temperatures [10]. Purified water was used to prevent mineral buildup, and the water level was maintained to cover the heating element. A thermometer ensured the temperature remained consistent within ±0.1°C. Samples were submerged in 200ml of water in a beaker placed in the bath, and the process was repeated three times per sample. The water temperature was set to a certain degree, which is 60°C, 80°C, and 100°C. The time for shape recovery was recorded using a digital stopwatch, effectively demonstrating the polymer's shape memory functionality under heat stimuli. The view of hot water equipment is shown in Figure 2.

The experimental design of the project is aimed at understanding the effects of various printing parameters and heat stimuli on the time taken for shape recovery of 3D-printed samples. This study evaluates the interaction and individual contributions of factors such as print speed, infill density, and post-printing water temperature on the recovery performance of printed samples. The study conducted 27 experimental runs, each tested 3 to 5 times for accuracy, to evaluate shape recovery behavior over time. Variables such as print speed, infill density, and post-printing water temperature were adjusted, while other parameters, including layer height, infill pattern, and nozzle diameter, were kept constant to ensure consistent results. The study investigates the effects of print speed (40, 70, 100 mm/s), infill density (30%, 60%, 90%), and post-printing water temperature (60°C, 80°C, 100°C) on the recovery performance of 4D-printed samples. The heat stimuli, applied via different water temperatures, simulate post-processing conditions to trigger the shape recovery behavior of the samples. This setup ensures a realistic assessment of the samples' performance under various environmental conditions. A full factorial design of $3^3 = 27$ experiments was implemented for ANOVA analysis using Minitab software. The details of the experimental configurations for each combination of printing parameters and heat stimuli, including the levels of print speed, infill density, and water temperature, are documented in Table 1 to provide clarity and reproducibility.

Table 1. Setting of Printing Parameters and External Stimuli.

Number	Printing speed (mm/s)	Infill density (%)	Water temperature after printing (°C)
1	40	30	60
2	40	30	80
3	40	30	100
4	40	60	60
5	40	60	80
6	40	60	100
7	40	90	60
8	40	90	80
9	40	90	100
10	70	30	60
11	70	30	80
12	70	30	100
13	70	60	60
14	70	60	80
15	70	60	100
16	70	90	60
17	70	90	80
18	70	90	100
19	100	30	60
20	100	30	80
21	100	30	100
22	100	60	60

23	100	60	80
24	100	60	100
25	100	90	60
26	100	90	80
27	100	90	100

Statistical analysis using ANOVA analysis was employed to identify optimal printing speed, infill density, and water temperature after printing for shape recovery based on the functionality time taken. The relationship between the parameters had significantly influenced the shape recovery behavior.

3. RESULTS AND DISCUSSION

In this section, the results are presented and discussed in relation to the objectives. Throughout multiple continuous experiments by using appropriate equipment to measure and control the possible outcomes, the result obtained from various set of combinations of the variables displayed weightiness different with each other. The discussed results had been divided into three subsections, corresponding to the objectives of the study. The gap between layers on the printed structure was obtained from Scanning Electron Microscope (SEM) analysis. Figure 3 was the sample of printing speed of 100mm/s, while Figure 4 indicates a sample of 40mm/s print speed. Both infill densities are the same, which is 30%. The figures show the measurement of the difference in the gap between the layers. 3 measurements were obtained to get the average length between layers on sample 7. On average, the gap was equal to 197.361. For sample 1, the average length of the gap between layers was 421.010. This means that a slower printing speed leads to a lower difference in the gap between layers of the printed structures. So, the shape recovery is much shorter with a slower printing speed as the layers are closer to each other.

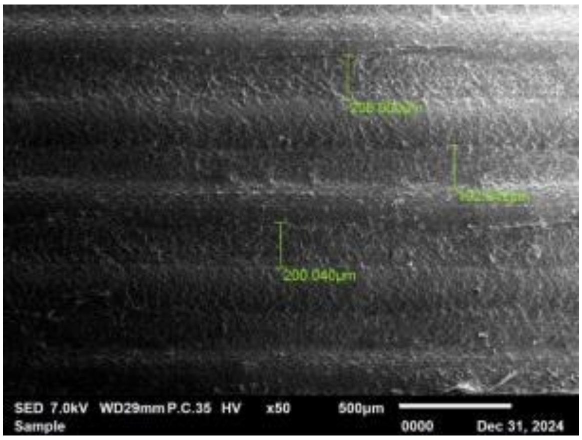

Fig. 3. SEM for Sample 1 (V=40mm/s)

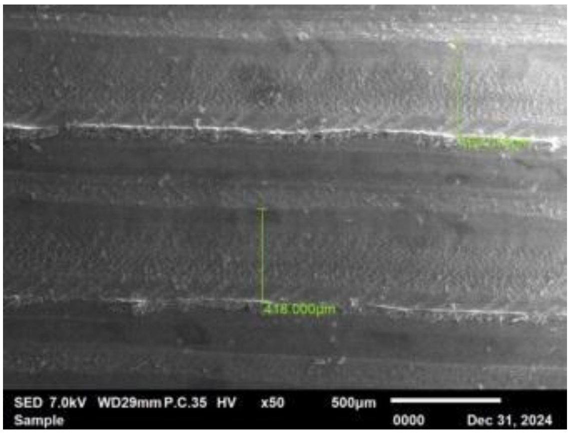

Fig. 4. SEM for Sample 7 (V=100mm/s)

In terms of infill density, the material within the structure was justified through SEM analysis (Figures 5 and 6). By using the same magnification, both figures were observed to have a different number of layers. With a constant speed of 100mm/s, the gap between layers was slightly different. But, the material within the structures can be seen as sample 9 has 5 layers in the magnification of zoom times 50, while sample 3 has 2 to 3 layers only. This concludes that a sample with higher infill density results in a higher number of layers within the material structures when zoomed in at the same magnification of 50 times.

Water temperature after printing does not alter the material structure but significantly affects its shape recovery behavior. Exposure to temperatures above the glass transition temperature (~60°C) can correct deformations but may cause warping, dimensional changes, or irreversible damage with prolonged exposure. Higher temperatures can degrade mechanical properties, reducing strength, flexibility, and overall performance.

Evaluation of Recovery Time under Heat Stimuli

The results obtained and summarized from Taguchi analysis are shown in Table 2. Different combinations of printing speed, infill density, and water temperature after printing led to different functionality time taken for shape recovery.

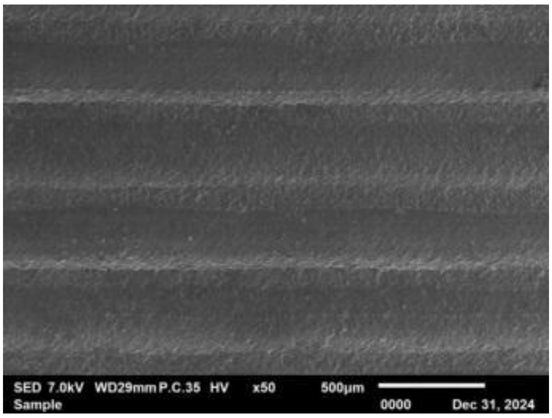

Fig. 5. SEM for Sample 9 (infill=90%)

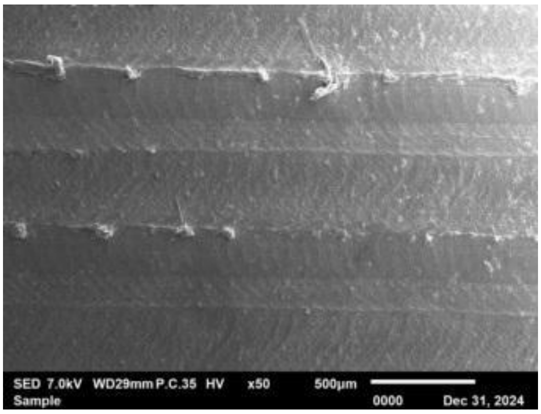

Fig. 6. SEM for Sample 3 (infill=30%)

Table 2. Functionality Time Recovery

Number	Printing speed (mm/s)	Infill density (%)	Water temperature after printing (°C)	Time taken (s)
1	40	30	60	29.04
2	40	30	80	16.84
3	40	30	100	7.27
4	40	60	60	38.55
5	40	60	80	17.41
6	40	60	100	8.71
7	40	90	60	53.58
8	40	90	80	18.89
9	40	90	100	10.37
10	70	30	60	28.64
11	70	30	80	14.34
12	70	30	100	10.33
13	70	60	60	37.54
14	70	60	80	15.53
15	70	60	100	11.78
16	70	90	60	53.46
17	70	90	80	17.11
18	70	90	100	13.09
19	100	30	60	26.79
20	100	30	80	15.20
21	100	30	100	7.32
22	100	60	60	35.59
23	100	60	80	16.31
24	100	60	100	8.87
25	100	90	60	51.28
26	100	90	80	17.01
27	100	90	100	9.95

Taguchi Design Analysis

This study discusses the result of functionality time taken for the printed parts to recover to its original shape with different settings of printing parameters and external stimuli. The discussion mainly comes from the Minitab software by using the Taguchi method. Analysing Taguchi consists of ANOVA analysis to find the response table for means. The optimal parameter settings for printing and water heating had been determined through a response table for means, as it ranks the variable accordingly. This study also disputes the effects of printing speed, infill density, and water temperature after printing on the material structures.

Table 3. Analysis of Variance of all Variable

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	4402.19	1467.40	36.46	0.001
Printing Speed	1	8.46	8.46	0.21	0.651
Infill Density	1	439.76	439.76	10.93	0.003
Water Temp after Printing	1	3953.98	3953.98	98.23	0.001
Error	23	925.76	40.25		
Total	26	5327.96			

The table of variance analysis in Table 3 shows that the p-value of water temperature after printing is 0.001. This value magnifies that this variable plays the uppermost role in affecting the time taken for the printed part to recover its original shape. F-value for water temperature after printing is almost reaches 100, which is 98.23. The larger the F-statistic, the greater the variation between sample means relative to the variation within the samples. A higher f-value leads to a lower p-value. This result emphasizes that there is a significant difference between the group means.

Response table for means shows how the mean value of a response variable, which is the time taken for shape recovery, changes across different combinations of printing parameters and water temperature after printing. This table provides an analysis of how these three factors influence the functionality time recovery of the printed parts.

Table 4. Response Table for Means of each Variable

Level	Printing Speed	Infill Density	Water Temp after Printing
1	22.296	17.308	39.386
2	22.424	21.143	16.516
3	20.924	27.193	9.743
Delta	1.500	9.886	29.642
Rank	3	2	1

Based on the response table for means in Table 4, the variables had been ranked accordingly. The variable that comes first to dominate the response time is water temperature after printing. Water temperature after printing has a delta value of 29.642, which is higher than the other two variables. With this support, it is best to justify that water temperature after printing is the most affecting factor in response to recovery time for the printed part to transform back to its original shape. The lowest mean response for printing speed was 20.924 at 100mm/s, where faster printing may improve efficiency as the shape of the printed parts needs a lower time to recover. Meanwhile, the infill density of 30% had the lowest mean, which leads to a more responsive shape recovery. The functionality time recovery is most sensitive to changes in water temperature after printing, as it has the highest delta value, which is 29.642. Infill density is not as impactful as water temperature after printing, but has a significant influence on the response, while printing speed has the least impact due to the smallest delta, suggesting its effect is relatively minimal compared to other factors.

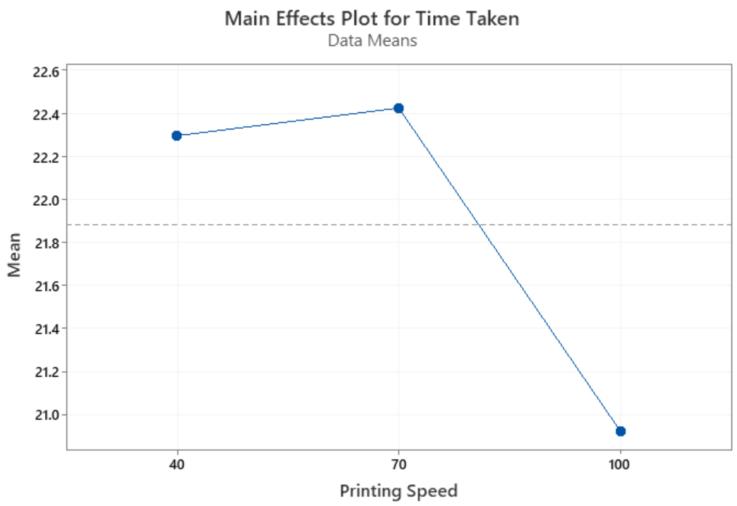

Fig. 7. Relationship between Printing Speed and Time Taken for Shape Recovery

The correlation of printing speed for time recovery is shown in Figure 7. The figure indicates the trend mean slightly increased from 40mm/s to 70mm/s and rapidly fell when printing speed was 100mm/s. When the printing speed was 70mm/s, the mean for recovery functionality time was at its highest. It was lower at 40mm/s speed and lowest at 100mm/s, which highlights a huge difference. Higher print speed, which is 100mm/s, results in the shortest time taken, indicating that increasing speed can enhance the efficiency of shape recovery. However, other factors such as print quality or material properties may need to be considered. A longer printing time, as seen at lower speeds like 40mm/s and 70mm/s, allows better cross-linking. The shape recovery can be enhanced as it creates more stable shape memory networks. Although the recovery functionality time was much faster at 100mm/s than the other two values, the precision on shape recovery is reduced due to incomplete bonding between layers.

Figure 8 displays the effect plot of infill density for the time recovery of the samples. Opposite to the previous variable, the graph plot of infill density shows the gradual increment for the different values, which are 30%, 60%, 90%. This trend states that higher infill density leads to slower recovery time. Due to the significance of the p-value, which is 0.003, infill density has a valid effect on the material's shape transformation. Higher infill density offers more material forms within the structure of printed samples. Logically, when the mass of the material within the structure is higher, the flexibility of the part becomes more rigid and firm. The printed part can be said as more difficult to bend or squeeze, which results in more time taken to recover its original shape. Stress concentration occurs when the stress at a specific point in a material exceeds the average stress. This may be due to irregularities in the material, such as holes or sudden changes in cross-section.

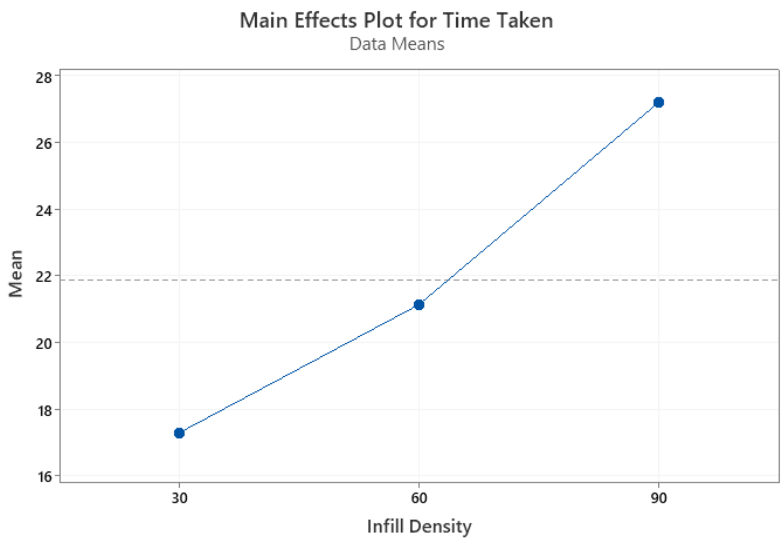

Fig. 8. Relationship Between Infill Density and Shape Recovery Time

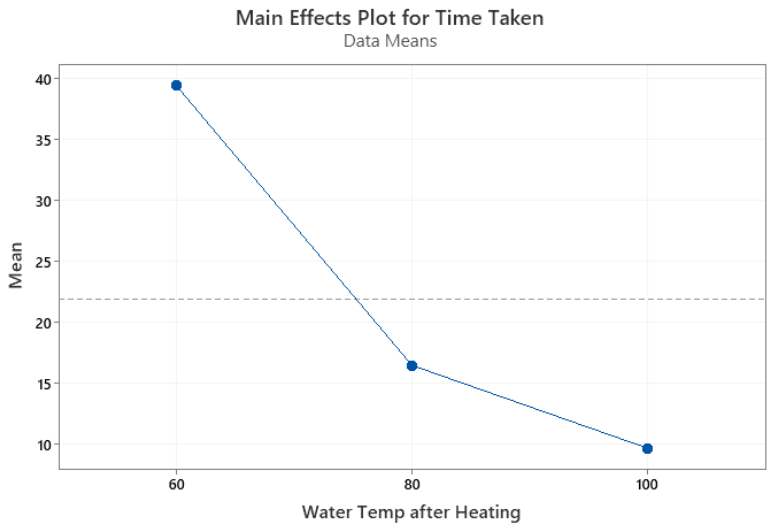

Fig. 9. Relationship between Water Temperature after Printing and Time Taken for Shape Recovery

Look back at the response table for means, water temperature after printing was ranked as number 1. This indicates that this variable is the most dominant in affecting the shape transformation capability of the printed structure part. Note that the capability of the printed structure parts to recover their shapes highly depends on the degree of the water temperature. The capability to transform back starts at the transition glass temperature, which for this material is 60°C. If the temperature is below 60°C, the material cannot activate the transformation. As suggested on the effect plot between water temperature after printing and time recovery, 60°C leads to slower recovery, while at 80°C and 100°C are faster and fastest, respectively. This is because 60°C is the minimum degree of temperature to activate the shape transformation capability of the material. It takes more time to trigger the material to start recovering its shape. For 80°C, the time taken for shape recovery was much shorter than when the temperature was 60°C. The fastest time for functionality time recovery was at a water temperature of 100°C. This correlation indicates that higher temperature leads to shorter time taken for shape recovery, as shown in Figure 9.

Based on the analysis, the optimal parameters for achieving the fastest and most effective shape recovery are a printing speed of 40 mm/s, 30% infill density, and a post-printing water temperature of 100 °C. At low printing speed reduces recovery time is reduced due to improved interlayer adhesion and more uniform layer formation, which enhances the shape memory response. Water temperature plays the most dominant role, with higher temperatures significantly accelerating shape recovery due to increased molecular mobility above the glass transition threshold (60 °C).

4. CONCLUSIONS

This study focuses on optimizing printing parameters like speed, infill density, and heating temperature to achieve effective shape transformation capabilities in shape memory polymers. The objectives include investigating the effects of printing parameters on material structures, observing functionality time recovery, and determining the optimal combination of variables for shape transformation. ANOVA analysis indicated that the optimal settings were a low printing speed, low infill density, and high water temperature, which together produced the shortest recovery time. However, improvements include careful handling of equipment, real-time process monitoring, time management, and proper guidance for equipment use.

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