ViviClay: Designing and Fabricating Ceramics with Animation Effects on Physical Surfaces

Guanhong Liu
College of Design and Innovation, Tongji University
Shanghai, China
liugh23@tongji.edu.cn

Jingxin Ye*
College of Design and Innovation, Tongji University
Shanghai, China
yejingxin515@gmail.com

Qiaoqiao Jin*
College of Design and Innovation, Tongji University
Shanghai, China
2151577@tongji.edu.cn

Chao Yuan
College of Design and Innovation, Tongji University
Shanghai, China
chaoyuan.idvx@gmail.com

Xuechen Li
College of Design and Innovation, Tongji University
Shanghai, China
primav1022@tongji.edu.cn

Yang Shi
College of Design and Innovation, Tongji University
Shanghai, China
shiyang1230@gmail.com

Qing Chen
College of Design and Innovation, Tongji University
Shanghai, China
Qingchen@tongji.edu.cn

Nan Cao†
College of Design and Innovation, Tongji University
Shanghai, China
nan.cao@gmail.com

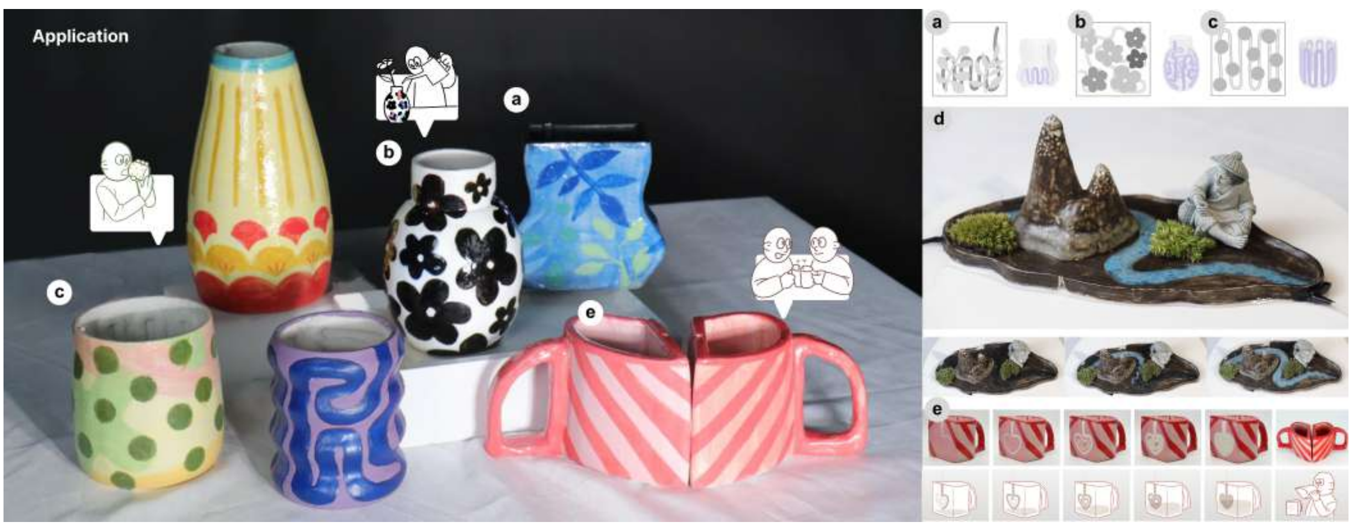

Figure 1: **ViviClay is a design and fabrication method that combines thermochromic coatings with internal pipe structures to produce dynamic, temperature-responsive animations on ceramic surfaces. Panels (a)–(c) present drinkware-inspired vessels, each accompanied by its internal pipe layout and corresponding 3D model shown on the right. Panel (d) illustrates Karesansui, a conceptual ceramic artifact designed for ambient display, shown alongside keyframes of its color-change animation. Panel (e) features one of the paired vessels titled Share Half with You, also accompanied by its animation keyframes.**

*Both authors contributed equally to this research.
†Corresponding author.

UIST '25, Busan, Republic of Korea

Abstract

We present ViviClay, a design and fabrication method that integrates thermochromic coatings with internal pipe structures to

ACM ISBN 979-8-4007-2037-6/2025/09
https://doi.org/10.1145/3746059.3747728

produce dynamic surface effects on ceramics. By channeling thermal fluid through embedded pathways, the surface exhibits reversible color changes, enabling animated patterns that are more programmable and varied than those of conventional thermochromic mugs. To address challenges in 3D printing clay—such as deformation and pipe clogging—we propose key design strategies, optimize fabrication parameters, and introduce a relief-style technique for curved surfaces. Building on this method, we develop a software tool and a set of structured design exemplars to support diverse form exploration while lowering design barriers. We demonstrate its potential through conceptual prototypes inspired by everyday everyday fluid interaction. This work represents the first exploration of 3D-printed ceramics that enable animated surface behavior in HCI, opening new directions for interactive and expressive ceramic practices.

CCS Concepts

• **Do Not Use This Code → Generate the Correct Terms for Your Paper**; *Generate the Correct Terms for Your Paper*; Generate the Correct Terms for Your Paper; Generate the Correct Terms for Your Paper.

Keywords

Clay 3D Printing, Thermofuidic Composites, Ceramics, Human Material Interaction

ACM Reference Format:
Guanhong Liu, Jingxin Ye, Qiaoqiao Jin, Chao Yuan, Xuechen Li, Yang Shi, Qing Chen, and Nan Cao. 2025. ViviClay: Designing and Fabricating Ceramics with Animation Effects on Physical Surfaces. In *The 38th Annual ACM Symposium on User Interface Software and Technology (UIST '25), September 28-October 1, 2025, Busan, Republic of Korea.* ACM, New York, NY, USA, 18 pages. https://doi.org/10.1145/3746059.3747728

1 Introduction

Dynamic displays and color-changing interfaces have been widely explored in HCI. A growing body of work integrates these technologies into everyday materials such as paper [19, 44], plastic [23, 25], and fabric [1, 37, 38]. While these approaches have expanded the expressive potential of common substrates, ceramic surfaces remain largely underexplored in this context. As a material with rich formal and tactile qualities, ceramics offer unique opportunities for embedding dynamic visual behaviors. Integrating thermal-responsive effects into ceramics opens up new directions for physical interaction and surface-based communication. Prior HCI research on clay 3D printing has primarily focused on improving fabrication quality [8, 13, 47], developing novel material systems [2, 4, 15], and enhancing interaction during the design and printing process [9, 18, 26]. However, the potential of ceramics as a medium for dynamic display remains largely unexplored.

In this paper, we introduce ViviClay, a design and fabrication method that enabling ceramic capable of generating animated effects on physical surfaces. Leveraging the waterproof and thermal conductive properties of ceramics, we explore the integration of internal pipe structures within ceramic walls. By directing thermal fluid through these internal pipes, heat is transferred to the ceramic surface, triggering temperature-induced color changes in the thermochromic coating and thereby creating dynamic animation effects. Although Thermotion [50] has demonstrated a similar approach, where the flow of hot and cold fluid through internal pathways drives surface color changes, we cannot directly adopt Thermotion's fabrication technique.

When working with ceramic materials, we encounter numerous challenges. Regarding material properties, clay remains in a semi-fluid state during the 3D printing process, making it prone to collapse and clogging. After printing, the clay must undergo air drying and high-temperature firing to solidify into ceramics, during which issues such as cracking, deformation, and shrinkage may arise. In terms of fabrication techniques, the most commonly used method for ceramic 3D printing is fused deposition modeling (FDM), where clay is extruded in coiled layers to form the final shape. Unlike Thermotion, which employs SLA-based 3D printing to create fine and intricate internal pipes, this method imposes significant constraints on the level of detail achievable. These material and technical limitations necessitate the exploration of optimized printing parameters and methods tailored for clay, enabling us to refine the design space, develop design tools, and create application prototypes.

To address these challenges and achieve animated surface effects, we conducted an empirical study optimizing ViviClay's printing and forming parameters. We found that maintaining a 24%–28% clay moisture content and a nozzle diameter of at least 1.2mm significantly improves stability and final quality. For structural design, arched pipe cross-sections provide a wide, stable base to prevent collapse, while a relief-style method effectively solves clogging issues in curved structures. For animation effects, a 1.2mm wall thickness delivers optimal clarity, and pipe cross-sectional area determines effect duration. Additionally, minimizing self-intersections in single-stroke paths helps avoid flow resistance and clogging.

Building on clay's properties, we explored ViviClay's shape and animation effects in three dimensions: structural design, pigment application, and assembly. Surfaces are classified as flat or curved—flat surfaces accommodate Single- or Multi-stroke paths for semantic icons and expressive textures, while curved surfaces consider contour shape, generatrix type, and twisting to accommodate forms like cups and vases. We then investigated thermochromic pigment applications, from full-surface coatings to localized pattern painting with traditional glazes, enriching visual variety. Finally, an assembly-based approach—joining and polishing multiple components—expands shape possibilities beyond single-piece printing, enabling more complex and practical ceramic forms.

To make the design and fabrication of ViviClay more accessible, we developed a software tool based on Rhino 8 Grasshopper, integrating Python scripts for interactive simulation of flow pipes and animation effects. This tool simplifies the modeling process: users first select a flat or curved surface from provided presets, then adjust parameters—such as contour shape, size, generatrix type, pattern style, and path width—to quickly generate embedded pipe structures, and then preview the simulated animation effects. The system automatically generates model files tailored for ceramic 3D printing, incorporating optimal wall thickness and pipe geometry to prevent collapse or clogging, thereby reducing printing failures.

Finally, we propose several conceptual application examples that explore the expressive and interactive potential of dynamic ceramics. Leveraging the natural hydrophilic properties of ceramics, our prototypes introduce hot water into the walls of vessels (e.g., cup-like forms), allowing fluid to flow through internal channels embedded within the structure. As the thermal flow activates surface color changes, these designs create animated visual effects that enhance sensory engagement and emotional resonance. The examples include drinkware-inspired vessels, tea-culture ornaments such as tea pets, and animated ceramics for ambient display.

Our contributions are as follows:

- We introduce a design and fabrication method that embedding pipes within ceramic walls, utilizing thermal fluid to drive thermochromic coatings for animated effects, and overcome FDM clay printing challenges through optimized parameters and a relief-style printing method.
- We present a structured collection of design exemplars for both flat and curved surfaces, demonstrating ViviClay's potential for generating complex 3D forms and dynamic textures through embedded pipe pathways, pigment application, and assembly strategies.
- We develop a software tool that enables structure design, animation effect previews, and model generation for ceramic 3D printing, lowering the barriers to design and fabrication.
- We demonstrate diverse conceptual applications that highlight ViviClay's expressive potential in fluid-interactive ceramic forms, offering inspiration for future creative practice and interaction design.

2 Related Work

2.1 Innovations in Ceramic Craft within HCI

Ceramics, as versatile and functional materials, have become deeply integrated into everyday life, with increasing exploration and innovation in recent years. HCI researchers have started focusing on combining ceramics with interactive technologies, pushing them toward smarter and more responsive designs [36, 42]. For instance, Zheng et al. [51] embedded electronic circuits into ceramic surfaces, enabling dynamic displays, sensing, and heating functionalities, thereby creating interactive ceramic artifacts that actively participate in everyday household activities.

At the same time, advancements in 3D printing technology have revolutionized ceramic fabrication and opened new possibilities for interactive ceramic design. Dedicated ceramic 3D printers allow digital models to be directly formed without relying on traditional molds or manual crafting. Designers now leverage digital tools such as CAD software and 3D printing to explore more complex shapes, textures, and structures, enabling ceramics to adapt flexibly to diverse applications [39, 41]. Since Marcus et al. [22] and Sachs et al. [31] first proposed ceramic 3D printing in the 1990s, the technology has continuously evolved, resulting in various forming methods. Among these, deposition-based forming, which shares similarities with traditional fused deposition modeling (FDM), has become particularly popular in HCI. In this method, clay is delivered from a barrel to a nozzle and extruded layer-by-layer following a predetermined printing path. Current HCI research on deposition-based ceramic 3D printing primarily focuses on optimizing print quality, exploring novel printing materials, and enhancing interactive experiences during the printing process.

To optimize printing quality, researchers have developed specialized software to precisely fabricate complex forms by refining printing paths [3, 8, 11, 13, 47]. In exploring innovative printing materials, various approaches have been proposed to enhance material properties and expand design possibilities. For example, Jauk et al. [15] embedded filaments into clay strands to increase tensile strength, enabling complex overhangs and free-form lines. Buechley et al. [4] developed a metallic clay capable of producing ceramic objects with mechanical properties comparable to bronze components. Bell et al. [2] mixed clay with bio-based dough, adjusting their proportions to leverage the greater shrinkage of the dough during sintering, thus creating uniquely shaped ceramic artifacts. To enhance user experience during the 3D printing process, some studies enable direct user interaction through path drawing [9], joystick control [18], or visual interfaces [29]. Other research emphasizes increasing hands-on involvement; for instance, Moyer et al. [26] developed a Digital Pottery Wheel (DPW) that allows users to combine machine printing with manual crafting in ceramic creation.

The exploration of ceramics' dynamic display capabilities remains limited. Our work leverages ceramic 3D printing technology to create a novel type of ceramic that enables animated effects on its surface, advancing research in this area.

2.2 Tangible Color-changing Interface

In tangible interface research, color changes are recognized as crucial interactive feedback. With the continuous emergence of novel materials, HCI researchers have been exploring how to implement dynamic color-changing interfaces on both two-dimensional and three-dimensional surfaces [7, 17, 35].

Dynamic display and color-changing technologies typically depend on materials responsive to external environmental changes, enabling various color-change effects driven by external stimuli. Common mechanisms include thermal, optical, electrical, and fluidic driving methods. Specifically, thermal-driven methods utilize thermochromic materials sensitive to temperature changes, with heating circuits commonly employed to regulate temperature and achieve dynamic color transitions. Such techniques have been extensively applied to everyday materials like fabrics [1, 37, 38], paper [19, 44], and plastics [23, 25, 45]. However, because single electronic components usually control only localized temperature changes, achieving complex animated effects requires multiple coordinated components, significantly increasing circuit complexity. Optical-driven methods leverage photochromic materials, generating rich color changes under varying lighting conditions [16, 30, 34]. Electrical-driven approaches utilize electroluminescent materials that emit visible light under electrical stimulation, enabling dynamic visual effects [12, 27]. Fluid-driven mechanisms achieve dynamic color changes by adjusting the distribution of colored fluids within precisely designed fluid channels [5, 24]. For instance, Venous Materials [24] employ millimeter-scale fluid channels embedded in flexible materials, generating color-change effects driven by fluid pressure. Additionally, specialized chemical reactions can also produce dynamic colors; for example, Ishii et al. [14] embedded electrodes within wet objects, applying electricity to trigger

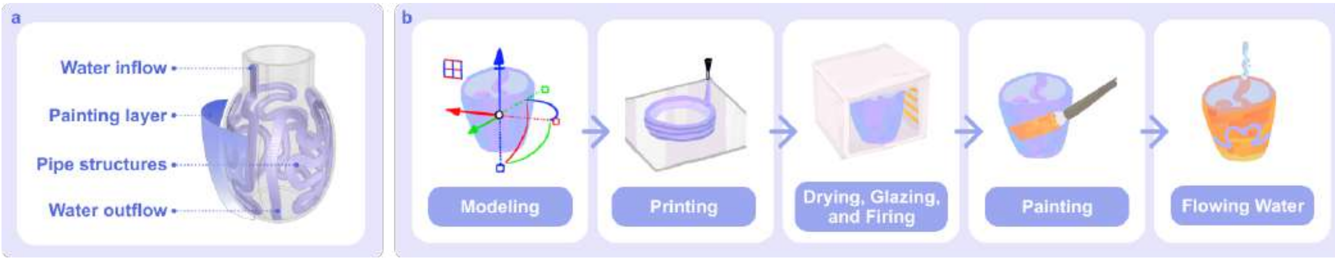

Figure 2: Overview of ViviClay. (a) The mechanism and structure of ViviClay. (b) Fabrication Pipeline.

electrolytic reactions on exposed wet surfaces, thereby producing colored patterns.

Our research leverages a thermofluidic-driven approach, eliminating the need for complex circuitry. By using thermochromic materials that sensitively respond to temperature changes induced by flowing fluids, we achieve dynamic textures on ceramic surfaces, introducing a novel color-changing interface to the field of tangible interaction.

2.3 Fabricating Interactive Objects with Embedded Fluidic Channels

In the HCI field, numerous studies have embedded fluidic channels within objects to enable diverse interactive functionalities. Common fabrication methods for objects with embedded fluidic channels include 3D printing, multi-layer composite assembly, and heat-sealed lamination.

3D printing is a widely adopted fabrication method that allows researchers to directly design intricate internal channel structures using CAD tools and precisely fabricate them through 3D printing technology. Printed objects can modulate air pressure through embedded channels to provide haptic feedback [33, 40], or achieve dynamic visual effects by filling channels with specific media [32, 50]. The essence of this approach lies in carefully designing internal channel geometries within CAD software to achieve desired interactive functionalities.

Multi-layer composite assembly is another fabrication method. Researchers use techniques such as molding, casting, laser cutting, and engraving [6, 10, 24, 43, 48, 49] to create intermediate layers with open fluidic channels. These intermediate layers are then bonded with encapsulating layers to form enclosed, three-dimensional internal fluid pathways. This approach involves fabricating complex intermediate layers and multiple-layer bonding, resulting in a relatively intricate overall process.

Additionally, researchers have explored heat-sealing methods to create embedded fluidic channels. This approach involves selectively applying heat and pressure along predefined paths, bonding multiple plastic film layers together in specific areas while leaving unbonded regions to form enclosed fluid channels [5, 20, 21, 28]. The key to this technique is precisely controlling the sealing process along designated pathways. This method is relatively straightforward, making it suitable for fabricating sheet-based fluidic structures.

Our research specifically optimizes the ceramic 3D printing process for clay materials. By carefully controlling critical parameters such as clay moisture content and nozzle diameter, and by introducing a relief-style printing method, we overcome common challenges like collapse and clogging during FDM printing. This approach enables the fabrication of interactive ceramics capable of displaying dynamic surface textures.

3 Overview of ViviClay Mechanism and Fabrication Pipeline

As shown in Figure 2-a, the core mechanism of achieving animation effects on the ceramic surface is to utilize the thermochromic paints' response to temperature variations. Specifically, we designed and printed ceramic objects with pipe structures inside walls. After firing, we apply thermochromic paints to the ceramic surface. When hot fluid flows through the pipes, the temperature change is transferred to the ceramic surface. Upon reaching a certain temperature threshold, the thermochromic paints undergoes a reversible color change. The ceramic surface can displays various dynamic textures on the different pipe pathways. The fabrication process of ViviClay consists of the following five key steps in Figure 2- b:

(1) **Modeling:** this step involves designing and modeling objects with pipe structures in their side walls. For flat and curved surfaces, we designed two set of printing methods, as mentioned in Section 4.3.
(2) **Printing:** this step involves using FDM clay 3D printing technology to fabricate the objects.
(3) **Drying, Glazing, and Firing:** after printing, the objects must be air-dried to remove moisture. Decorative glaze can then be applied to the surface, followed by firing at 1240℃ to solidify the form into finished ceramics.
(4) **Painting:** considering the limited accessibility of food-safe thermochromic pigments and encapsulation coatings used in commercial color-changing ceramic mugs, we adopted a more accessible alternative to validate the fabrication workflow. A water-based thermochromic pigment with a transition temperature of 31℃ was applied to the ceramic surface, followed by a layer of water-based clear varnish as a sealant. As both materials are not heat-resistant, they were applied after the ceramic was fully sintered and cooled.
(5) **Flowing Water:** to trigger the dynamic surface textures of ViviClay, hot water at 40℃ is injected through the internal channels. The fluid used is pure water, consistently heated to the target temperature using a thermostatic water bath, and injected immediately to ensure thermal consistency.

4 Empirical Studies on Printing and Structural Design of ViviClay

In this section, we will report on the challenges of pringting ViviClay, and the experiments on key parameters of printing and structure.

4.1 Challenges

During the fabrication of ViviClay, we face two primary challenges: (1) the difficulty of printing and forming, and (2) the design and control of its animation effects.

Clay moisture content, along with the structural and morphological design of ViviClay, are key factors influencing forming quality. The main difficulties stem from clay's semi-fluid state during printing, which makes collapse, deformation, and channel blockage likely; further shrinkage and distortion during drying and firing can compromise channel clearance and dynamic textures. Maintaining an appropriate moisture content keeps the extruded clay stable and minimizes deformation risk, while well-considered channel geometry helps prevent collapse or breakage from unsupported stacking, thus reducing the chance of blockage.

Pipe dimensions, wall thickness, and path geometry are also crucial factors for achieving animated ceramic effects. We hypothesize that wall thickness—specifically the thin material layer between the internal pipe and the object's outer surface—and pipe size both impact how the animation shows, though experimental validation is needed. Moreover, while certain pipe paths may appear theoretically feasible, water flow can be disrupted in practice, leading to unexpected deviations from the intended texture. These issues warrant further investigation.

4.2 Experimental Setup

The clay used in this study is white porcelain clay with a firing range of 1240–1300°C. Its main components include kaolin, clay minerals, quartz, and mica. After firing, it typically undergoes a shrinkage of approximately 10%.

For the printing process, we use the STSW-3040 ceramic 3D printer manufactured by Digital Ceramics Technology Co., Ltd. (Changsha, Hunan, China), which operates via pneumatic extrusion[1]. During printing, the air pump pressure is maintained at approximately 0.65 MPa to ensure extrusion stability. 3D models are created using Rhino and Grasshopper, and slicing is carried out using Simplify3D. Printing is performed on either plaster boards or glass sheets covered with plastic wrap to mitigate the risk of cracking caused by uneven shrinkage during drying.

4.3 Study on Forming and Structural Design

In this section, we explore how to 3D print clay objects with embedded fluid pipes, focusing on both printing stability and structural design.

4.3.1 ***Study on Stable Clay 3D Printing.*** We found that the clay's moisture content and nozzle diameter directly affect the stability of extruded coils, thereby influencing the overall quality of ViviClay prints.

On one hand, moisture content is critical to the 3D printing and forming process. If the clay is too wet, its high fluidity causes deformation during printing, and taller structures may collapse due to insufficient strength. Conversely, overly dry clay tends to break during extrusion, and layer-to-layer adhesion deteriorates, leading to compromised print quality.

To determine the appropriate moisture content, we prepared clay samples with varying water ratios and conducted printability tests to identify optimal formulations. Moisture content was calculated using the ratio of dry to wet weight, with suitable samples falling within the 24%–28% range. For each new batch, we measured the penetration depth of a Vicat needle dropped from a fixed height to verify consistency in hardness. To ensure uniform moisture distribution and eliminate air bubbles during loading, the clay was mixed using a dual-shaft vacuum pugmill.

On the other hand, small solid particles in the clay often clog narrower nozzles, resulting in print failures. Our experiments showed that, for this specific white clay, a nozzle diameter of at least 1.2mm effectively reduces the chance of clogging and maintains continuous, stable extrusion under our current setup.

4.3.2 ***Study on Structural Design for Flat Surface Printing.*** During the flat printing process, we used a finer extrusion head (1.2mm nozzle) to create detailed pipe structures. For the same texture pattern, we tested four shapes—square, circle, triangle, and arch—each with a maximum width and height of 4mm (see Figure 3). Slicing was set to 100% infill with a Rectilinear pattern.

From the top view, square pipes easily caused the upper clay coils to drop due to the lack of a tapered top, making this shape unsuitable. In contrast, circular, triangular, and arch-shaped pipes showed fewer collapse issues. However, side views revealed that all shapes experienced some compression distortion from the clay's semi-fluid nature during extrusion. Because clay shrinks further after firing, triangles were ruled out due to sidewalls collapsing inward, compromising the cross-sectional area. Between circular and arched cross-sections, we found that an arch has a flatter, wider base, improving contact with water and promoting clearer thermal color changes. Consequently, we chose the arch shape as the optimal design.

4.3.3 ***Study on Structural Design for Curved Surface Printing.*** When printing pipes on curved surfaces, we initially tried embedding them directly within the curved form. However, this approach struggled to produce continuous, unobstructed pipe structures in practice. Because the pipes are hollow, their upper coils must span a distance without solid support, and given clay's semi-fluid state, extended spans often deform or break—and may even drop into the hollow pipe below (Fig. 4-a). Once a small-diameter pipe experiences any collapse or distortion, it is easily blocked. Moreover, clay undergoes shrinkage during drying and firing, so smaller pipes risk becoming too narrow and compromising fluid flow. Although enlarging the pipe size can offset shrinkage, it also increases wall thickness, limiting the applicability of certain curved designs.

To address these issues, we introduced a relief-style printing method (Figure 4-b). Specifically, we designed an arched pipe structure that "floats" above the curved surface and modeled the object's

[1] http://www.bingzhe.net/h-col-886.html

Figure 3: Different pipe shapes and their printing conditions.

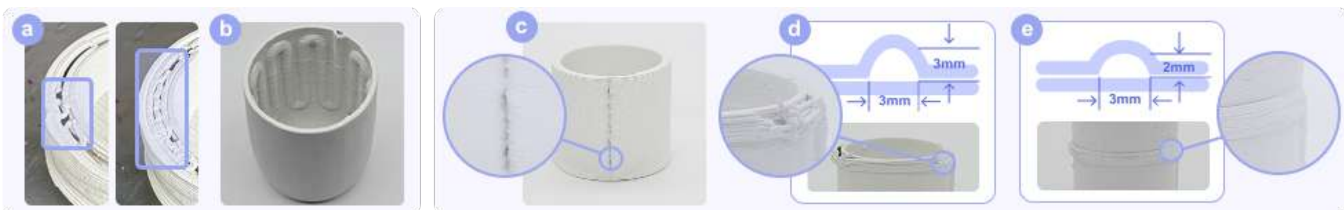

Figure 4: Experiments on printing pipes on curved surfaces. Two different methods for printing pipes: (a) printing pipes within the curved surface, which proved unfeasible. (b) Printing pipes using a relief-style method. Challenges encountered during the relief-style printing process: (c) fixed layer start points may cause visible seams at joints. (d) A steep angle at the highest point of elevated arched channels makes them prone to deformation and fracture during printing. (e) Suitable pipe form and parameters for the relief-style printing method.

thickness as twice the nozzle diameter. During slicing, we set infill to 0 and shell count to 1, so only an inner and an outer wall are printed. The outer wall remains flat to preserve the object's overall shape, while the inner wall bonds with the outer wall in non-pipe areas and forms a raised channel in pipe regions. Experiments showed that this approach consistently yields pipes with unobstructed interiors.

In practice, we encountered additional challenges. First, if each layer starts at the same point, a noticeable seam forms at the joint, risking fractures (Fig. 4-c). To address this, we configured the slicer to randomize the starting point for each layer, dispersing any seam accumulation. We also found that the geometry of the arched pipe heavily affects print quality, especially for horizontal pipes. Since the clay remains semi-fluid during printing, steep arches often deform, misalign, or break (Fig. 4-d), disrupting subsequent layers. In contrast, flatter arches print far more reliably (Fig. 4-e).

4.4 Study on Animation Effects Design

This section examines how pipe dimensions, wall thickness, and path geometry affect the resulting dynamic textures.

4.4.1 ***Study on Effects of Wall Thickness and Pipe Size on Animation.*** We found that wall thickness (the minimal layer between the internal pipe and the object's external surface) and pipe size both affect the animation. To explore this, we printed the same arched pipe path on multiple 10cm×10cm flat surfaces, each uniformly coated with a thermochromic pigment that turns colorless

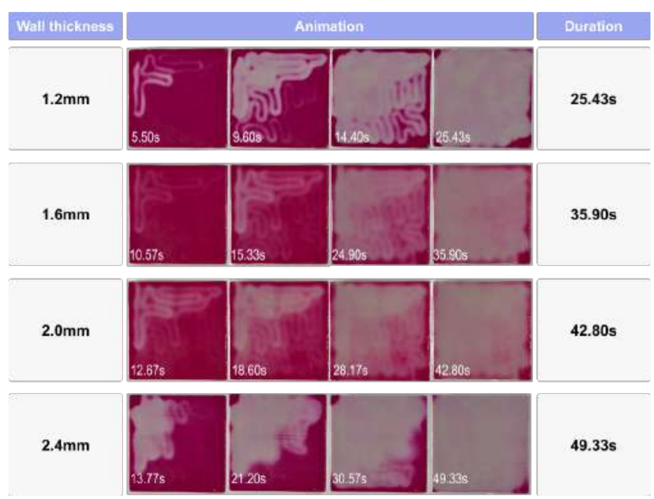

Figure 5: Experiment on the Influence of Wall Thickness on Animation: We collected data at four observation points with similar animation progression under four different wall thickness conditions, recording both the current and total animation durations. Our findings indicate that as wall thickness increases, animation duration becomes longer, and texture clarity decreases.

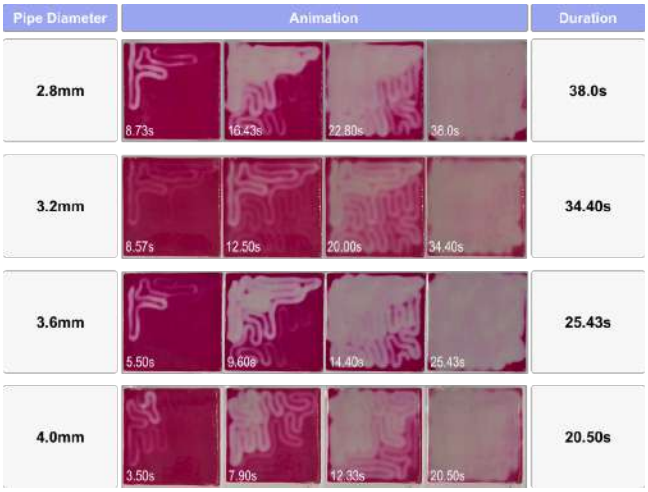

Figure 6: Experiment on the Influence of Pipe Size on Animation: We collected data at four observation points with similar animation progression under four different pipe diameters, recording both the current animation duration and the total duration. Our findings indicate that as the pipe diameter increases, the animation duration decreases.

at 31°C. Only the pipe cross section and wall thickness were varied, with the water flow rate held constant, allowing us to observe how these parameters influence the dynamic texture.

For the wall thickness study, we kept the pipe's base diameter at 4mm and height at 3.6mm, then varied the distance between the pipe base and the ceramic surface to produce four thicknesses (1.2mm, 1.6mm, 2.0mm, and 2.4mm). Repeated tests showed that as the wall gets thicker, the texture takes longer to form and the linear patterns become less pronounced. Once the wall thickness reached 2.4mm, the surface primarily displayed large, continuous gradient regions along the pipe's path rather than distinct line patterns (Fig.5).

For the pipe size study, we fixed the pipe's base diameter at 4mm to maintain a consistent texture path width and used a 1.2mm wall thickness, as determined in previous experiments. The pipe heights were set to 2.8mm, 3.2mm, 3.6mm, and 4mm, matching the 0.4mm layer height in slicing. Repeated water-flow tests showed that all pipe sizes produced clear, linear dynamic textures, but the animation duration slightly decreased as the pipe's cross-sectional area increased. Under a constant flow rate, a larger cross section allows more water to pass per unit time, accelerating the effect and thus shortening the display period. Consequently, pipe size primarily influences the animation's duration (Fig.6).

4.4.2 ***Study on Effects of Path Shape on Animation.*** We also examined how path geometry affects fluid-driven textures using several one-stroke paths, including semantic icons without intersections (defined in Section 5). For instance, the "&" symbol and a tailed cat design contained extensive intersecting segments that blocked water flow, while the lightbulb—despite having a small intersection—successfully delivered smoother animation(Fig.7) . Our observations suggest that when water reenters a pipe at longer intersecting segments, local pressure builds up, increasing flow resistance and potentially causing blockages. Hence, to maintain the intended texture, one-stroke paths should avoid or minimize the length of crossing sections.

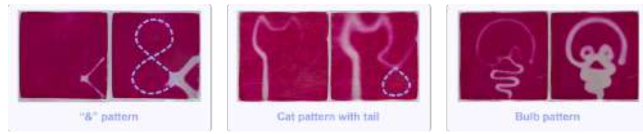

Figure 7: Three different single-stroke paths with self-intersections were examined. The first two paths feature longer loops after their self-intersection points, making it difficult to fully display the complete path changes. However, the bulb-shaped path has a shorter loop following its self-intersection point, allowing the animation to be presented completely.

4.5 Summary of Study Results

This section experimentally examines key factors affecting forming quality and dynamic textures in ViviClay. Results show that maintaining a clay moisture content of 24%–28% ensures stable extrusion and forming. Flat structures used a 1.2mm nozzle (line width 1.2mm, extrusion multiplier 1, layer height 0.4mm); curved forms used a 1.5mm nozzle (same multiplier/layer height). Print speed was 30mm/s, reduced to 15mm/s for first layers and shells. The first-layer line width was set to 120% for sealing. On flat surfaces, arched pipes with a wide, flat base and ample heat conduction area yield clear, stable dynamic textures. For curved surfaces, embedded pipes often collapse or clog, whereas our relief-style method significantly boosts stability and maintains open channels. Additionally, a 1.2mm wall thickness facilitates crisp texture rendering, while pipe size primarily affects the animation's duration. Path geometry studies indicate that one-stroke paths should avoid lengthy intersections to prevent local pressure buildup and blockages. These findings provide a foundation for further design and optimization of ViviClay.

5 Design Library and Examples

Our aim is not to develop an animation-style system (as exemplified by Thermotion [50]), but rather to investigate which structural configurations can be practically fabricated in clay while still enabling basic dynamic effects. To better understand the material constraints and expressive potential of clay-based dynamic surfaces, our design library explicitly distinguishes between flat and curved geometries. This distinction is not merely taxonomic—it reflects fundamental differences in fabrication strategies and structural feasibility within the context of FDM-style clay 3D printing.

Flat structures are built layer by layer in the XY plane, allowing internal channels to be reliably formed by sandwiching flow paths between a base and a sealing layer. In contrast, curved forms—such as cup-like vessels—require continuous extrusion along complex 3D contours, with channels embedded between inner and outer walls. These geometries pose substantially greater risks of clogging, deformation, or collapse, due to the thixotropic nature of clay and the challenges of unsupported overhangs.

In addition, by combining different thermochromic pigment application methods, diverse animated effects can be achieved on ceramic surfaces. We also introduced an assembly process to effectively expand the shape space, enabling the fabrication of more complex three-dimensional forms.

5.1 Shapes and Animation Effects Exploration

5.1.1 ***Flat Surface Structures and Effects*.** In exploring the shapes and animation effect on flat surface, we classify the channel paths into two main categories based on their structural features and dynamic texture effects: Single-stroke paths and Multi-stroke paths shown in Figure 8.

Firstly, Single-stroke paths refer to pipe structures consisting of a single continuous channel, allowing fluid to flow continuously from the inlet to the outlet. According to the characteristics of the resulting textures, single-stroke paths are further divided into three sub-types:

- *Semantic Icons without intersections:* Paths designed as recognizable icons (e.g., heart or arrow) that clearly convey semantic meanings. These paths do not contain any intersections to ensure continuous fluid flow and stable pattern presentation.
- *Semantic Icons with intersections:* Paths similarly designed as semantic icons, but containing at least one intersection point. It should be noted that single-stroke paths containing intersections have certain limitations, as not all such paths can successfully display complete animation effects along the entire path. This issue was discussed in Section 4.4.2.
- *Expressive Textures:* Paths primarily designed to produce diverse and visually appealing dynamic effects rather than convey specific semantic meanings. Examples include horizontal or diagonal wiping, radial spreading, and growing curves.

Secondly, Multi-stroke paths consist of multiple parallel or interwoven channels through which fluid simultaneously flows, creating more complex and richer animation effects. Currently, multi-stroke paths exclusively focus on Expressive Textures, such as regular and irregular mesh patterns, aimed at generating expressive dynamic visualizations.

5.1.2 ***Curved Surface Structures and Effects*.** In exploring the shapes and animation effects on curved surfaces, we classify the structures based on three key geometric characteristics: contour shape (Circular vs. Non-circular), generatrix type (Straight line vs. Curve, where the generatrix refers to the line that sweeps along a path to form the surface), and twist behavior (Twisted vs. Not twisted), as shown in Figure 9. Each structure type is embedded with single-stroke paths to show its impact on the animation effect.

Firstly, Circular structures refer to shapes with a circular contour, meaning the cross-section remains circular along the entire height of the object. These structures can be further classified based on the type of generatrix:

- *Straight-line generatrix, Cannot twist:* The structure is formed by a circular contour and a straight-line generatrix. Due to the rotational symmetry of the circular cross-section, even if the object is twisted around its central axis, its appearance remains unchanged. Therefore, these structures inherently cannot exhibit twist deformation.
- *Curve generatrix, Cannot twist:* Similar to the straight-line generatrix, these structures are formed by a circular contour but with a curved generatrix. However, because the cross-section remains circular, rotating around the central axis does not alter the overall shape, making twist deformation impossible.

Secondly, Non-circular structures refer to shapes where the contour is not circular, allowing for more geometric variations. These structures can also be classified based on the type of generatrix:

- *Straight-line generatrix, Not twisted:* The non-circular cross-section extends along a straight generatrix without rotation, maintaining a consistent orientation throughout the height.
- *Straight-line generatrix, Twisted:* The non-circular cross-section rotates around the central axis as it extends along the straight generatrix, introducing a twisted effect that alters the overall shape.
- *Curve generatrix, Not Twisted:* The non-circular cross-section extends along a curved generatrix without rotation, resulting in a smoothly curved shape while maintaining the same cross-section orientation.
- *Curve generatrix, Twisted:* The non-circular cross-section both follows a curved generatrix and rotates around the central axis, leading to a more complex twisted form that impacts the fluid-driven animation effects.

5.2 Animation Effects with Different Painting Methods

Thermochromic pigments come in two types: colored-to-colorless (Fig.10-a) and colorless-to-colored (Fig.10-b). The colored-to-colorless type can be mixed with regular pigments, and in its colorless state, the mixture appears as the color of the regular pigment. Creators can apply the pigments in either of the following two ways:

Flat Painting. The thermochromic paints are evenly applied across the entire ceramic surface (Fig. 10-a & b). This approach allows the ceramic surface to display dynamic displays that correspond to the pipe path shapes when water flows through.

Patterned Drawing. Thermochromic paints and glazes are used to create patterns on the ceramic surface (Fig. 10-c). Creators can draw arbitrary patterns with glaze on the ceramic surface, and thermochromic paints are then applied to specific areas after firing. The strategic combination of glaze patterns and thermochromic paints enables a more expressive presentation of temporal dynamic effects.

5.3 Assemble Design space into Compound Shapes

Due to the molding limitations of clay materials during the printing process, the clay remains in a semi-fluid state, making it prone to collapse and deformation. If one intends to print complex channel structures on an object's surface using a monolithic fabrication method, the design space is confined to the range shown in Figure 9.

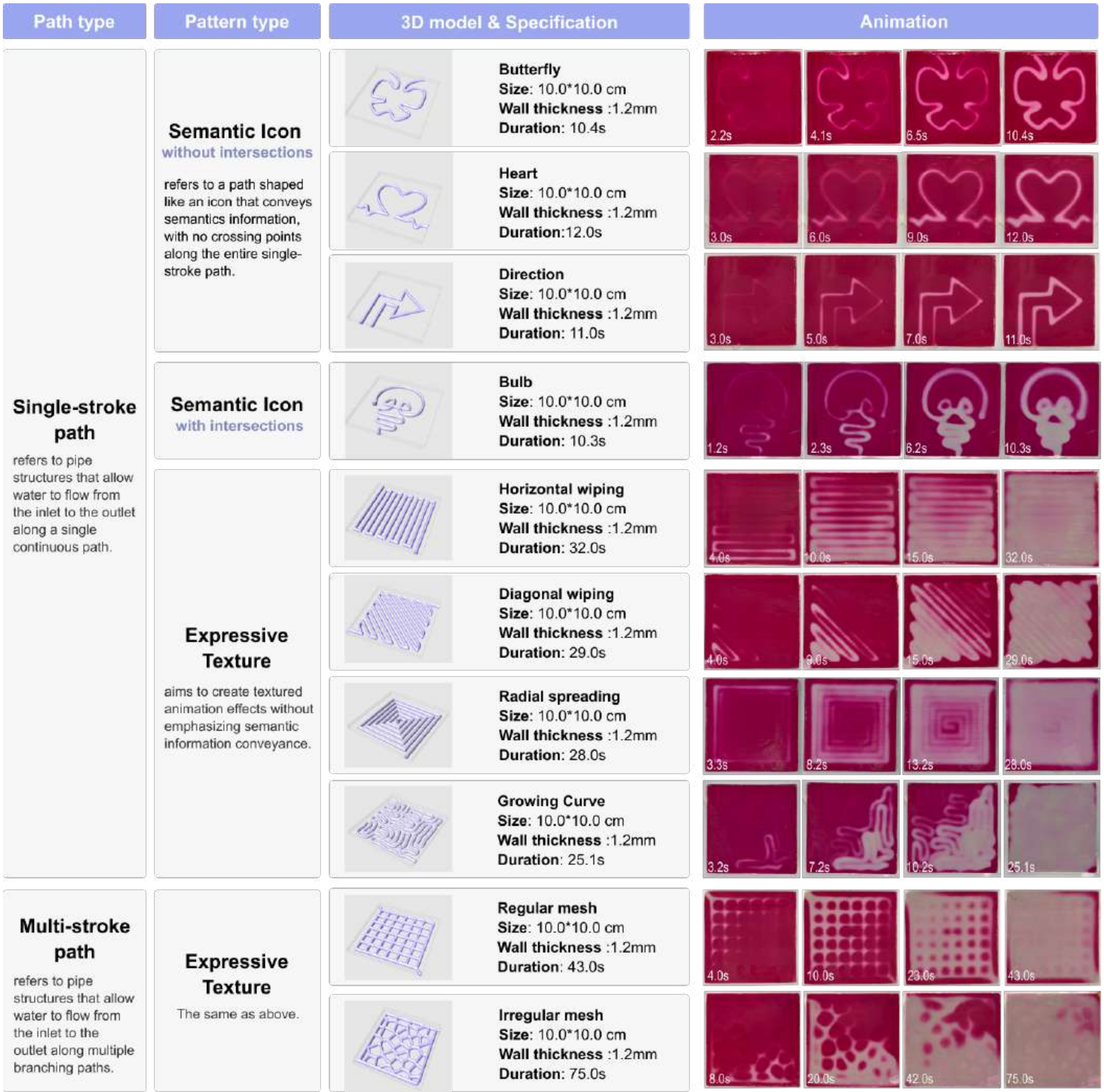

Figure 8: Shapes and animation effects on flat surfaces. The critical color-changing temperature of the thermochromic paint applied to the surface is 31°C, while the temperature of the water flowing through is 40°C. The wall thickness and size refer to the dimensions used during 3D printing.

Currently, the relief-style printing method is only suitable for printing simple pipeline structures on the surfaces of three-dimensional objects that feature smooth and gentle curves, such as cups and vases. To further expand the possibilities of ceramic shapes, we introduced an assembly process. By combining the design space of flat surfaces (Figure 8) with diverse hand-crafted or 3D-printed components, one can fabricate compound shapes with dynamic textures. Flat surfaces with internal pipes can serve as essential elements of three-dimensional objects—such as cup walls, bases, or decorative features—as demonstrated in the case study in Section 7.

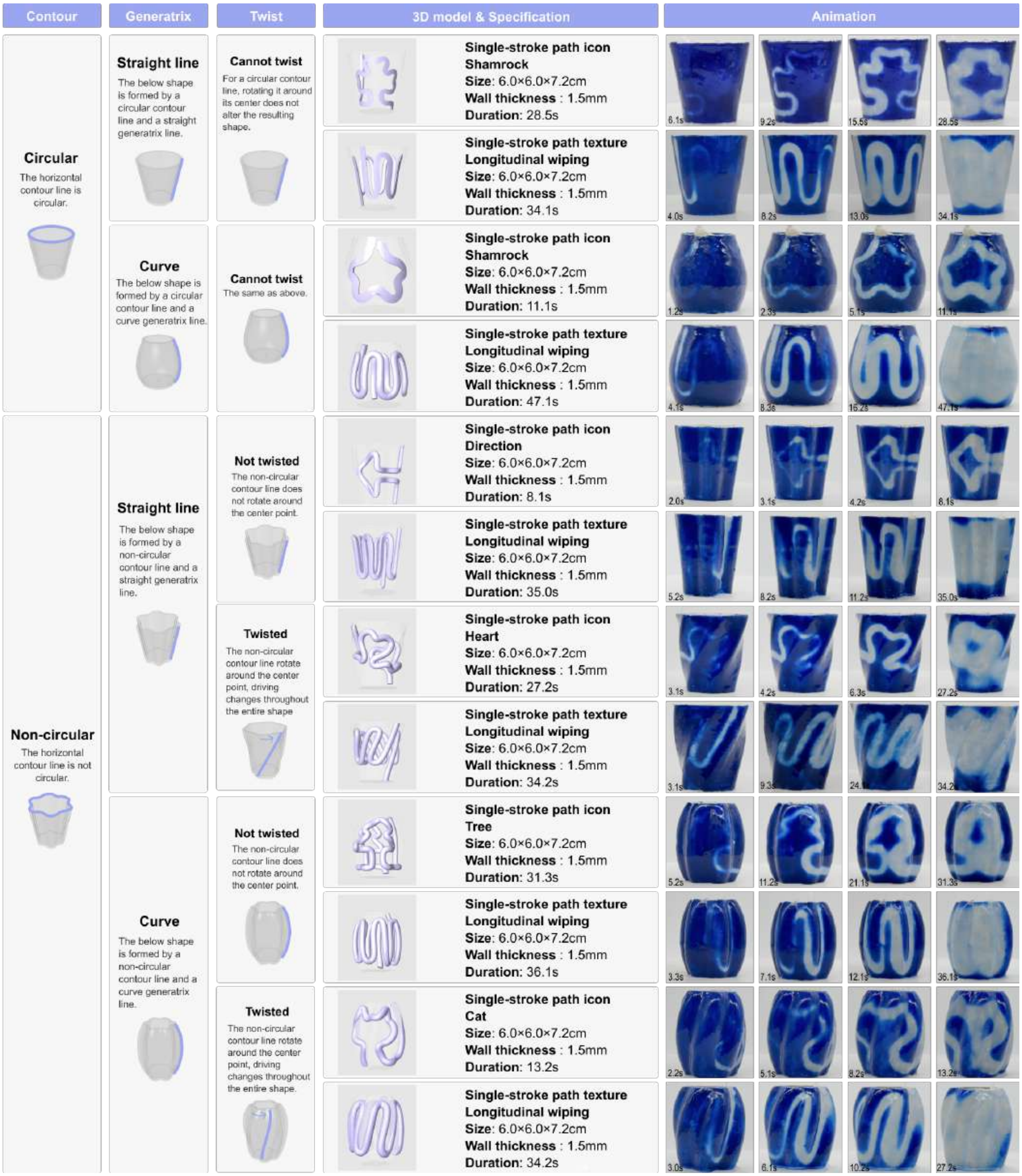

Figure 9: Shapes and animation effects on curved surfaces. The critical color-changing temperature of the thermochromic paint applied to the surface is 31°C, while the temperature of the water flowing through is 40°C. The wall thickness and size refer to the dimensions used during 3D printing.

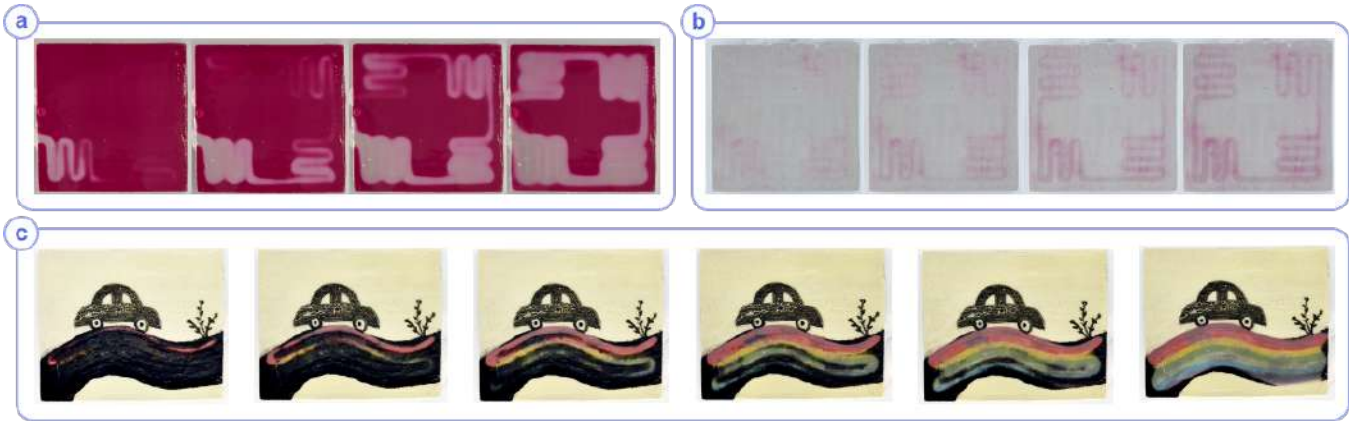

Figure 10: Two different application methods: (a,b) flat painting and (c) patterned drawing. (a) Applying thermochromic paint that transitions from colored to colorless on the ceramic surface. (b) Applying thermochromic paint that transitions from colorless to colored on the ceramic surface. (c) Drawing patterns on the ceramic surface using thermochromic paint and glaze.

Figure 11: Detailed three steps of assembly process. (1) Preparation – includes (a) preparing the objects for assembly and (b) mixing the clay slip to the appropriate consistency. The clay must be mixed to achieve an appropriate clay slip consistency. If the clay slip is too thin, the bonding will be weak; if it is too thick, it becomes difficult to apply, potentially causing gaps at the connections and increasing the risk of cracking; (2) Assembly – includes (c) evenly applying the prepared clay slip to the contact surfaces and (d) assembling the parts into a compound shape; (3) Polishing – involves (e) using a damp sponge to smooth the seams, ensuring they are even and visually appealing.

The detailed fabrication process involves three steps—preparation, assembly, and polishing—as illustrated in Figure 11.

6 Design Tool of ViviClay and User Workflow

To assist designers in creating animated effects with ViviClay, we developed a customized design tool for shape creation, pattern design, and animation simulation（shown in Figure 12). The tool provides essential forms and templates derived from the established design space, enabling diverse designs and animations through simple parameter adjustments. Users can conveniently preview simulated animation effects and export digital files suitable for subsequent fabrication processes. The tool is implemented in Rhino 8's Grasshopper environment, with a custom Python extension developed to support animation simulation.

6.1 Step One: Shape Design

6.1.1 ***Flat Surface Shape Design***. The construction of a flat surface is determined by its external contour shape. In the current design, flat surfaces are primarily intended for modular assembly, serving as dynamic bases or ceramic walls. We provide five common external contour shapes to meet basic assembly requirements, including Circle, Square, Hexagon, Cloud, and Wave. The area of the flat surface affects the layout and printing quality of internal channels. Surfaces with overly small areas are insufficient to accommodate complex internal channels, whereas excessively large areas are prone to cracking during the drying process. Therefore, we have restricted the surface area. After selecting the external contour, users can further choose from three preset sizes: small (100 cm^2), medium (140 cm^2), and large (180 cm^2).

6.1.2 ***Curve Surface Shape Design***. The construction of a curved surface is determined by its contour shape and generatrix. Due to the constraints of clay 3D printing, the tool currently supports curved surfaces with gentle curvature and smooth transitions. Thus, we provide five preset contour shapes—Circle, Square, Hexagon, Cloud, and Wave—each featuring low curvature and smooth edges. For the generatrix, we offer three gently varying options: Vertical, Inclined, and Arc. Combining these contour shapes and generatrices results in 15 basic printable forms. Users can further adjust the radius and height to modify the overall size. Additionally, non-circular contours can be twisted around their central axis to create new variations; therefore, we include a Twist option, allowing users to activate or deactivate this feature.

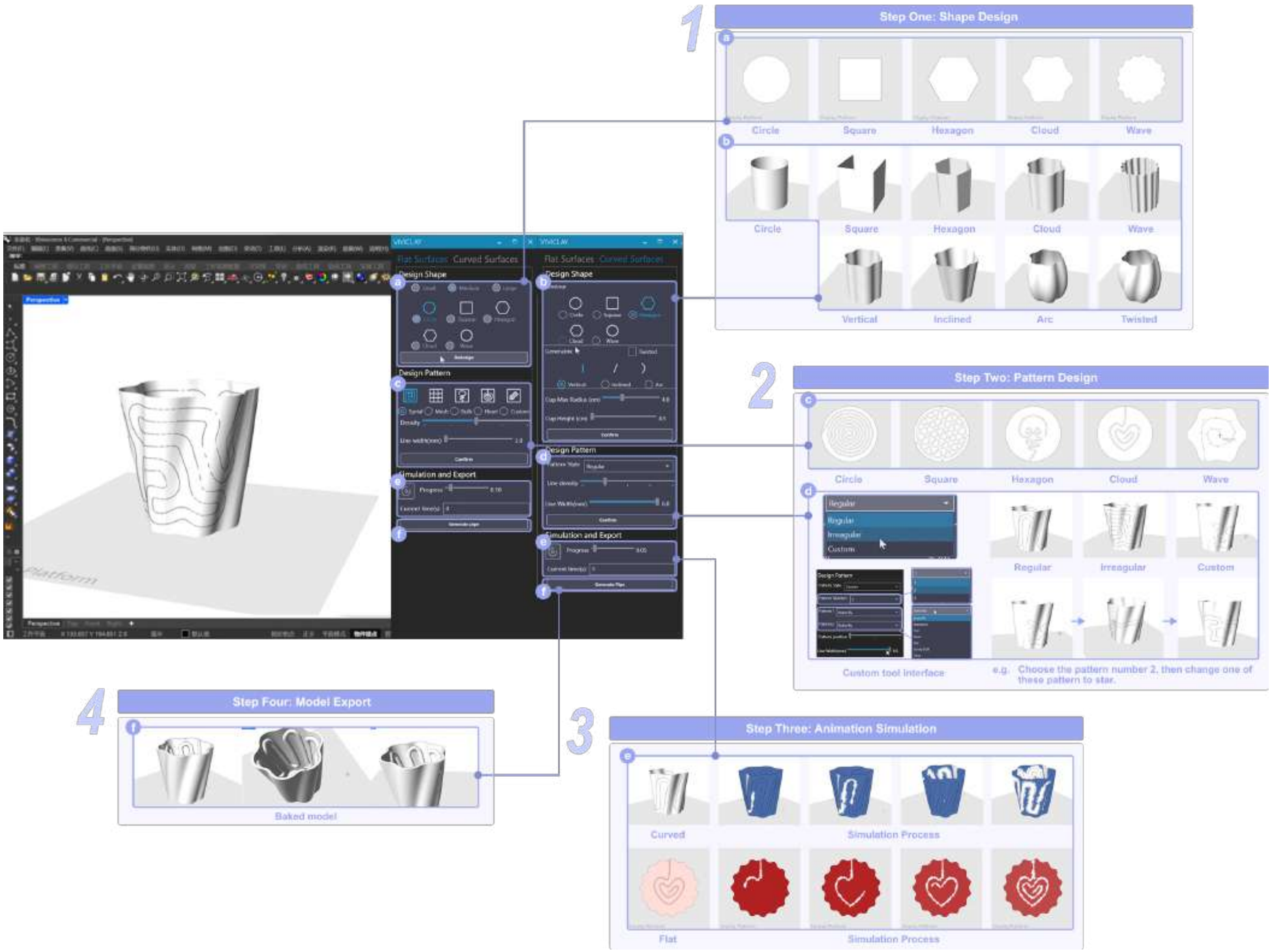

Figure 12: The design tool and user workflow of ViviClay.

6.2 Step Two: Pattern Design

6.2.1 ***Flat Surface Pattern Design.*** For flat surfaces, printing internal pipe structures is relatively straightforward, enabling greater design diversity and personalized expression through user-defined patterns. We provide four preset patterns: two textures—*Spiral* and *Mesh*—and two semantic icons—*Bulb* and *Heart*. Users can adjust certain parameters (e.g., density) for texture-based patterns; see Figure 8 for animation examples. These presets feature one inlet/outlet at the top and one or more inlets/outlets on the sides, making them suitable for modular assembly. The tool also supports user-defined patterns for one-stroke paths. The tool automatically detects the distance between the user-drawn path endpoints and the outer contour: if this distance is less than 1 cm, the tool extends the path to form side-wall pipe openings connecting to the contour; if greater than 1 cm, it generates top-wall pipe openings.

6.2.2 ***Curve Surface Pattern Design.*** For curved surfaces, unsupported clay filaments during 3D printing can easily cause collapse or deformation, making it challenging to ensure the feasibility of fully user-defined patterns. Thus, we provide three preset pattern modes based on our established design space. The first mode features regular vertical variations along the cup wall, allowing users to adjust pattern density and path width. The second mode extends randomly across the curved surface to cover the entire cup wall, with user-adjustable path width. The third mode offers predefined symbols—including Butterfly, Shamrock, Tree, Heart, and Star—from which users can select up to three patterns to combine sequentially and adjust their path width. Users can also position these patterns at the bottom, middle, or top of the surface.

6.3 Step Three: Animation Simulation

After the shape and internal pipe structure have been determined, users can preview the color-changing animation by clicking the "Play" button. If unsatisfied with the current animation, users can click the "Redesign" button on the previous step panel to modify shape and pattern parameters. This iterative process can be repeated until the desired animation effect is achieved.

We provide a basic animation simulation for ViviClay, allowing users to preview animation effects during the design phase. Precise simulation remains challenging due to factors such as gravity, pouring methods, and container shapes, which significantly affect water flow—especially for curved surfaces. Given that the primary applications of ViviClay (e.g., tea pets and cups) emphasize macro-level animation effects rather than highly accurate fluid dynamics or heat transfer, the practical benefits of more detailed simulations remain uncertain. Therefore, we use a simplified and easily implemented approximation approach, prioritizing practical design guidance over theoretical precision.

First, we simplify the target geometry into a mesh surface and compute the shortest surface distance between the heat sources and each mesh vertex using the geodesic distance field method, providing a foundation for subsequent heat diffusion calculations. Next, we construct a heat diffusion model: each heated source point diffuses heat to neighboring vertices, with the diffusion range determined by the baseline heat diffusion rate, the heating duration of the source, and a time-dependent attenuation property that gradually decreases over time. To simulate the sequential activation of heat sources along the flow path, we discretize the path into multiple potential heat-source points. Based on the known length of the flow path and empirically derived flow velocities, we establish a temporal sequence for activating each heat-source point, where earlier points activate sooner and have a larger diffusion range, while later points activate relatively later with smaller diffusion extents. By integrating the temporal activation characteristics, heating duration, and diffusion attenuation effects of heat-source points, we simulate the animation effect of ViviClay (see Figure 13).

Figure 13: Animation simulation effect of two typical shapes.

6.4 Step Four: Model Export

When users are satisfied with the animation effect, they can click the "Generate Pipe" button to create an object with embedded pipe structures. The tool automatically generates and bakes the corresponding model in Rhino, which users can then convert into G-code for 3D printing using slicing software. Our experiments in Section 4.4.1 indicate that clear dynamic textures are best achieved with wall thicknesses ranging from 1.2mm to 2mm. Thus, generated objects use a fixed default wall thickness—1.2mm for flat surfaces and 1.5mm for curved surfaces. For both surface types, the embedded pipe structures have a semi-elliptical cross-section, and models generated for curved surfaces are specifically optimized for relief-style printing.

7 Design Concepts and Possibilities

ViviClay is a ceramic fabrication method that uses flowing water to drive dynamic textures effects. the ViviClay system presents versatile potential for dynamic ceramic design. The fabrication workflow—comprising 3D printing, drying, glazing, and high-temperature firing at 1240°C—follows standard ceramic practices that ensure structural integrity and material durability. Although the thermochromic pigment and gloss coating applied post-firing are not food-safe, they serve as visual proof-of-concept and can be readily substituted with commercial food-safe coatings commonly used in temperature-sensitive tableware.

To acknowledge safety considerations, we refrain from making direct claims regarding food-related applications. However, the underlying process is inherently adaptable, opening the door to functional implementations such as drinkware, decorative tea pets, or ambient-responsive objects, with only minor material adjustments. The following section outlines conceptual design directions that highlight ViviClay's expressive and interactive potential.

7.1 Drinkware-Inspired Form Studies

In bookstores and cultural gift shops, creatively designed ceramic mugs—especially thermochromic cups that change color with temperature—are increasingly popular among young consumers. Currently, most thermochromic mugs are limited to simple cylindrical shapes with basic, single-directional effects, usually displaying gradual color changes from bottom to top. In contrast, ViviClay offers more diverse shapes and richer, programmable animations, delivering novel interactive experiences and greater visual appeal.

Figure 14-a shows a pair of conceptual vessels titled Share Half with You, created using the assembly method described in Section 5.3. The straight wall is printed as a flat surface with embedded channels, while the heart-shaped wall is printed without channels. When joined, they form a symbolic heart shape. A pink thermochromic pigment, which turns transparent upon heating, is applied to the straight wall. As hot water flows through the internal paths, a heart pattern gradually emerges—producing a poetic and emotional effect. While this prototype includes an internal outlet for fluid transfer, the focus remains on exploring visual interaction and symbolic composition. Similar configurations could incorporate other motifs—such as stars, cat silhouettes, or leaves—yielding vessels with diverse forms and layered meaning.

Figure 14-b presents two additional prototypes fabricated using relief-based printing. The top vessel features growth-curve-shaped channels with a blue thermochromic line applied along their path. As hot water flows through, the line fades, revealing a pink glaze beneath in a gradual, animated transition. The bottom vessel contains vertical serpentine channels and multiple thermochromic dots that become transparent at 31°C, creating a sequential fading effect from left to right that reveals underlying yellow glaze.

Figure 14-c shows two jar-shaped containers with dynamic visual effects. The top jar uses growth-curve channels beneath a black thermochromic layer, which gradually fades to reveal colorful floral patterns as hot water flows through. The bottom jar uses yellow thermochromic stripes along vertical serpentine paths that disappear sequentially with heat. While these prototypes conceptually suggest temperature-based interaction in container-like forms, their

primary purpose is to demonstrate surface animation and dynamic expression through controlled thermal flow.

7.2 Interactive Ceramics Inspired by Tea Pets

Tea pets are ornamental ceramic figures rooted in traditional tea culture, commonly made from purple clay, pottery, or porcelain. Often shaped as animals, mythical creatures, or auspicious symbols, they are placed on tea trays and symbolically bathed with leftover tea—representing good fortune and bringing playful charm to the tea ritual. With the revival of tea culture and growing interest among younger generations, tea pets have evolved into culturally expressive products that blend traditional craftsmanship with contemporary aesthetics.

Figure 15-a shows two tea pets prototypes created using the assembly method described in Section 5.3. Each design consists of two parts: a flat base panel containing internal pipes and an upper water-guiding container without pipes. This structure allows creators to freely design visual patterns on the base panel and various shapes for the water-guiding container, as long as tea flows smoothly. During use, tea poured into the container flows into the base through inlet holes, guided by internal pipes, and exits from side outlets, producing playful visual effects. The two tea pets shown have distinct creative themes. One adopts a parametric design, displaying a dynamic honeycomb-pattern spreading visually on the base. The other draws inspiration from a cat-and-mouse scenario, where pouring tea makes the black coating on top fade, gradually revealing a mouse pattern beneath, adding interactive fun.

Figure 15-b shows a tea pet prototype made with a monolithic printing process, featuring a square base and a vase-shaped body. The internal pipe is located at the lower front of the vase, where a leaf pattern is painted on the surface and coated with thermochromic pigment. Users can place decorative items like artificial flowers into the vase. When tea is poured in, it flows through the pipe, gradually fading the leaf pattern along the outer wall, creating an engaging and visually appealing interactive experience.

7.3 Animated Ceramics for Ambient Display

The above examples are based on natural water use, where gravity-driven water flow creates animated effects on ceramic surfaces without electricity. Alternatively, a powered water circulation system can be introduced to enable more diverse and controllable interactions. This involves integrating a compact control unit at the base, containing separate hot and cold water reservoirs. Each is equipped with a small peristaltic pump that activates based on specific triggers: hot water causes the thermochromic material to fade, while cold water restores its color.

Trigger conditions can be made more diverse—for example, integrating with decorative desktop stress-relief devices. When elevated stress is detected, the control unit can quietly activate the water circulation, gradually revealing dynamic textures on the ceramic surface. This offers a gentle, non-intrusive way to externalize the user's physical or emotional state.

Figure 15-c shows a decorative tabletop piece inspired by Karesansui (dry landscape gardens). Controlled by a pump, hot and cold water flow through small sidewall inlets and pass along serpentine pipes, triggering thermochromic fading to create a flowing river animation—evoking the tranquil scene of a fisherman immersed in nature.

8 Discussion, Limitations and Future Work

In this section, we will discuss about bridging material innovation and killer applications in HCI, and limitaions and future work of this study.

8.1 Envisioning the Practical Applications of ViviClay

In HCI, material- and fabrication-driven research typically follows a clear path: it begins with exploring physical mechanisms, proceeds to design spaces, simulation, and tool development, and concludes with demonstrative applications. Examples like Thermotion [50], Venous Materials [24], and WaxPaper [46] illustrate this trajectory. Fueled by curiosity about material behaviors, these studies highlight how material intelligence can merge with computation to deliver novel insights.

This research introduces a method for dynamic textured ceramics that integrates structural design in ceramic 3D printing with thermochromic mechanisms. We use users' everyday behavior—specifically, the familiar act of pouring hot water—as a natural trigger to activate animated visual effects on the ceramic surface. Leveraging the hydrophilic and heat-conductive properties of ceramics, our design transforms daily actions into sources of animation without relying on external electronics or complex sensing systems. In terms of interaction logic, this approach explores how physical behavior itself can serve as system input, embedding interaction into habitual routines and aligning with the design orientation of interaction-as-behavior. This reduces the complexity of technology integration and enhances the system's coupling with real-life scenarios.

The current prototypes serve as conceptual demonstrations. In future work, we aim to further develop the system toward real-world deployment. Given ceramics' long-standing cultural and functional role in contexts such as drinking, tea rituals, and home decoration, we envision two main application pathways: food-safe and non-food-safe scenarios.

Food-safe scenarios (e.g., drinkware): Commercial thermochromic mugs developed within Chinese cultural heritage IP systems—such as the Thousand Miles of Rivers and Mountains mug by the Palace Museum (Beijing) and the Nine-colored Deer mug from the Dunhuang Museum cultural series—have already adopted food-safe thermochromic pigments and are widely available in the creative market. For practical deployment, we plan to replace our current visual validation coatings with food-grade thermochromic materials and conduct additional material testing (e.g., strength, hardness) to ensure reliability. Since our designs incorporate internal piping, we also need to evaluate microbial safety and develop auxiliary cleaning tools for flushing the channels, ensuring hygiene in everyday use.

Non-food-safe scenarios (e.g., tea pets): Tea pets are ornamental items used in tea culture, where people pour leftover tea over them as a playful and symbolic ritual. This context is naturally well-suited to dynamic visual effects. Future work may focus on long-term

Figure 14: Color-changing process of the prototypes. (a) A pair of conceptual vessels named "Share Half with You" and the cheers scene. (b) Two cup-shaped prototypes made by relief-based printing. (c) Two jar-shaped containers.

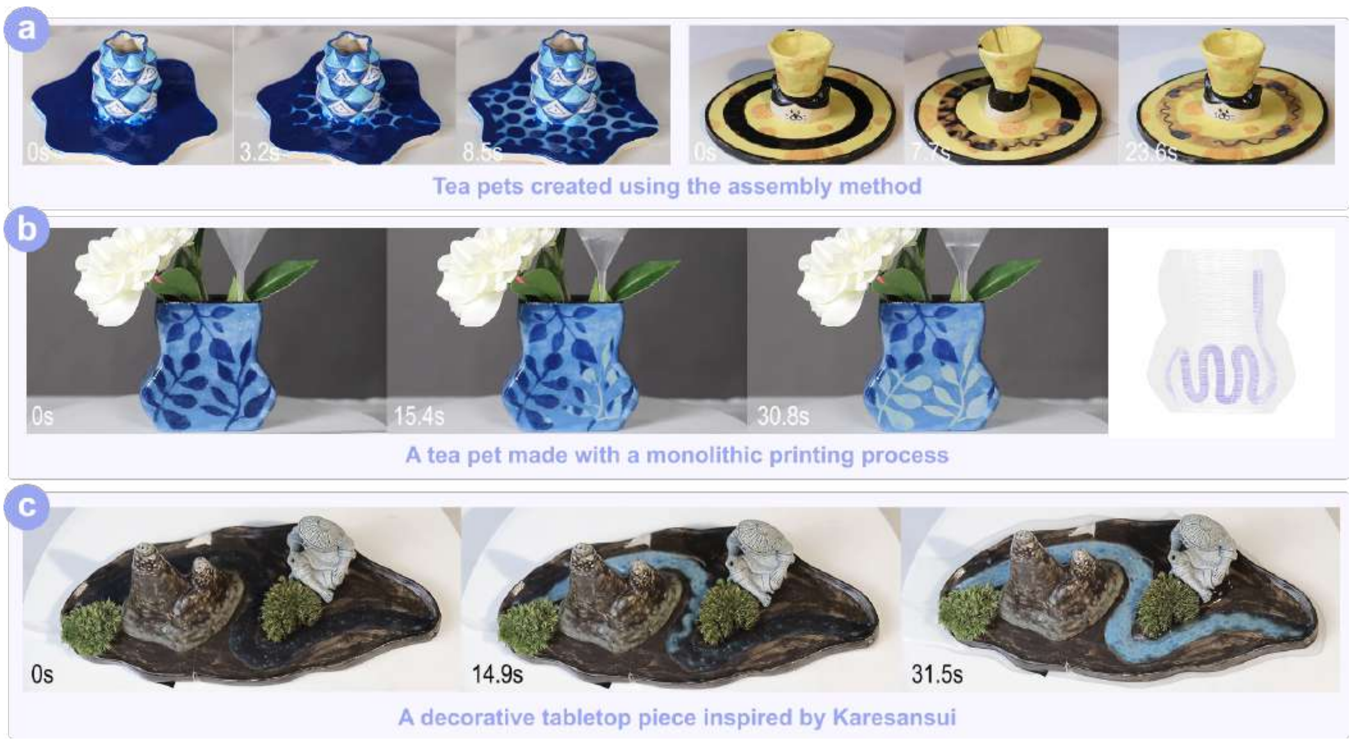

Figure 15: Color-changing process of tea pets prototypes and tabletop piece. (a) Tea pets prototypes created using the assembly method. (b) A tea pet prototype made with a monolithic printing process. (c) A decorative tabletop piece inspired by Karesansui (dry landscape gardens).

durability of materials and further explore aesthetics, narrative design, and IP collaboration—for example, co-designing limited-edition or branded tea pets in partnership with cultural institutions or traditional artisans, merging heritage craft with digital ceramics.

Educational and creative applications: ViviClay also holds strong potential for educational outreach, such as in maker education, parent-child activities, or workshops combining ceramics and technology. With intuitive design tools and a low-barrier printing workflow, participants can engage in the full process of material-based creation, including parameter tuning and visual feedback, fostering cross-disciplinary creativity and broadening public understanding of interactive ceramics.

In summary, this work proposes an interaction method driven by everyday behavior and material responsiveness, while envisioning its translational potential in drinkware, cultural derivatives, and maker education. Future development will address material safety, cleaning challenges, and co-creation mechanisms, advancing the integration of digital craftsmanship and HCI.

8.2 Limtations and Future Work

The limitations and potential directions for future work are as follows. First, the geometries we have explored so far are relatively simple. Moving forward, we plan to experiment with more complex 3D structures, such as combining wave-like contours and generatrices, to push the performance limits of clay 3D printing and broaden the possibilities for dynamic textures.

Second, the current design tools can be further optimized. As the design space grows, more template options will be needed; at the same time, the accuracy of the simulation tool still needs improvement. We aim to adopt a data-driven approach by conducting extensive controlled experiments to record how different pipe shapes, flow rates, and other variables affect the animated effects. These data will then be used to build predictive models with deep learning, thus enhancing the realism of our simulations.

Third, no systematic user study has been conducted yet. In the future, we plan to involve a broader range of participants—such as product designers, ceramic artists and practitioners—in the design and creation process. This will help enrich ViviClay's design cases and open up more diverse application scenarios.

9 Conclusion

This paper presents ViviClay, a ceramic fabrication method that enables animated surface effects by embedding internal pipe structures and applying thermochromic coatings. By channeling hot fluid through these pipes, the ceramic surface exhibits reversible color changes, producing dynamic textures beyond conventional bottom-to-top thermochromic animations. To address challenges in clay 3D printing—such as material deformation and pipe clogging—we propose structural strategies, optimize key fabrication parameters, and introduce a relief-style printing technique for curved surfaces. To support the design-to-fabrication process, we developed a software tool that enables users to design embedded pipe layouts, preview thermal animations, and generate printable models. We demonstrate a set of conceptual application examples—including drinkware-inspired vessels, tea pets, and ambient display objects—that illustrate the expressive and interactive potential of ViviClay. This work lays the groundwork for exploring dynamic behaviors in ceramic surfaces and contributes to broader inquiries into material-based interaction and digital making within HCI.

Acknowledgments

This work was supported by 1) Youth Fund for Humanities and Social Sciences Research, Ministry of Education 24YJCZH168; 2) NSFC 62372327, NSF Shanghai 23ZR1464700; 3) Fundamental Research Funds for the Central Universities. We also thank for Tianyu Yu, Danyang Song, and Xiaozao Wang for their eagerness to help.

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