ChromoFilament: Designing a Thermochromic Filament for Displaying Malleable States

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ABSTRACT

The 3D pen has become a popular crafting tool where hands-on deformations are largely engaged. However, as malleable states are invisible, users might be burnt, or their fabrication might fail. We designed a thermochromic 3D filament, ChromoFilament, that displays the malleable states in three different colors according to the associated temperatures. From color design workshops, we identified proper stages of malleability and design considerations for color combinations, which are applied to ChromoFilament. Next, we depict a way to fabricate ChromoFilament from customizing thermochromic ink to extruding with the coated pellets. Finally, we illustrate the users' distinctive behaviors with ChromoFilament to imply the effects of visible malleable states. We believe that our material-perspective approach, design process, and a series of findings could not only inspire supporting creativity through thermoforming but also heat-based processing in 3D printing.

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Fabrication; Creativity Support; Filament Design;

CSS Concepts

• Human-centered computing~Human computer interaction (HCI)

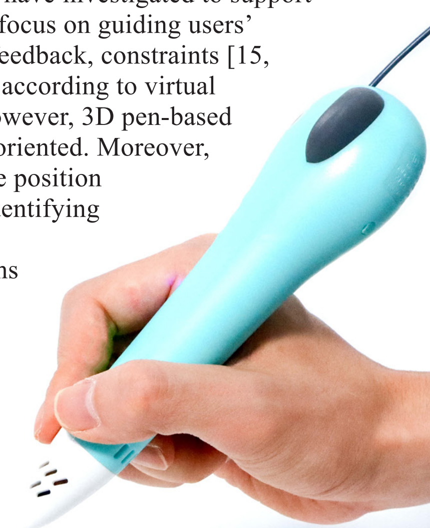
INTRODUCTION

A portable and inexpensive 3D pen like 3Doodler [1] has become popular in many fields such as a hobby, education, art, and design. Unlike other digital fabrication tools, 3D pens are manually controlled by users from the amount of extruded mass and extruding positions [26]. In addition, users can deform the extruded mass with their hands until it cools down. This way, users can doodle in a 3D space and express their creativity with a high degree of freedom.

As with most crafts, a 3D pen is simple to manipulate but requires many iterations and skillful experience to build 3D objects. One of the factors is that the malleable state of extruded parts varies with their temperature. On the bright side, users can either deform large parts or refine details by controlling the level of the malleable states. Unfortunately, a malleable state is hardly identifiable by observation. Although 3D filaments become glossy at high temperatures, it is subtle and inconsistent and can be affected by a light source and the properties of a filament. Thus, users can only weakly guess or touch the target surface, leading to fabrication failures or being burnt.

So far, many researchers have investigated to support creativity. Most of them focus on guiding users' position through haptic feedback, constraints [15, 19, 37] and visual traces according to virtual models [4, 6, 20, 22]. However, 3D pen-based fabrication is on-the-fly oriented. Moreover, printing in an appropriate position should be preceded by identifying malleable states. Finally, external hardware systems might constrain user behaviors.

Distinctively, we took a material approach, i.e., designing a 3D printable filament.



While not constraining user behaviors. ChromoFilament can be fabricated at a DIY scale by coating plastic materials with thermochromic pigments and extruding them by using commercialized filament extruders. ChromoFilament visually presents its malleable state, which could support both hands-on deformation and heat processing in 3D pen-based fabrications.

In this pictorial, we first reveal the typical process of 3D pen-based fabrication, and the problems caused by misidentifying malleable states. Second, through design workshops, we derived design considerations for displaying malleability during the 3D pen-based fabrication process . Third, we share the manufacturing process of DIY level thermochromic 3D filaments. Finally, we illustrate the fabrication process and particular behaviors of using ChromoFilament.

RELATED WORKS

Our research focuses on supporting craft with an interactive system, bringing unconventional 3D filaments in digital fabrication, and applying interactive colors. We ultimately aim to promote thermoforming in 3D printing contexts.

Interactive Fabrication for Supporting Craft

Interactive fabrication systems allow users to fabricate objects while interacting with the workpieces [5, 17, 18, 34]. Some of them supported human-based fabrication by providing physical or perceptual guidance. For example, machines control their milling speed [37] or give haptic feedback with constraints based on users' virtual models [15, 19]. Takahashi et al., proposed a system using both a 3D pen and a 3D printer where 3D printed parts could provide physical guidance [26].

Compared to other guidance, visual cues are less decisive where users can freely deviate from the cues. Being the mchaine guides users' fabrication with a laser pointer [4]. Similarly, Exo-skin indicates a visual cue on the body to allow users to extrude following the cue [6]. In mobile fabrication, researchers provided an app in which users can follow the trace on a tablet device with a 3D pen [22]. WireDraw is a mixed reality system that provides visual guidance for user fabricate with a 3D pen device [36]. Beyond the application of pre-defined deisgn, BodyStylus supports on-the-fly fabrication by controlling visual cue and ink [20].

We focuse on displaying the malleable state of printed parts during fabrication rather than guiding the position for extrusion. This would support most practical behaviors with a 3D pen. Besides, without an external device and a predefined model, users can doodle naturally with 3D pens.

Bringing Unconventional Materials in Digital Fabrication

To enhance printing capabilities, industry and academia have been investigating the printing of novel and functional materials. One possible approach is to develop a system that prints novel materials. Printing teddy bear is a system which prints 3D objects with soft fibers [8]. ReForm is a novel printer-oven system for printing a special polymer that becomes malleable when heated [33]. Printflatables is a system that seals vinyl in a programmable way [25]. Researchers developed a novel biomaterial [35] and applied it to a novel printing device which computationally extrudes them in the form of inkjet printers [31]. In ExpandFab, researchers presented 3D printing of a volume-expanding polymer by heating with custom 3D printers and explored the design space for expandable printed objects [10].

Building novel printers is difficult for end-users to apply. Moreover, they may not be compatible with the existing 3D printing infrastructure. Developing 3D printable filaments with the target material could be a possible solution to avoid these problems. Programmable filament allows users to produce multicolor filaments with an off-the-shelf single nozzle printer in a programmable way [27]. Similarly, we designed and implemented a 3D printable filament. Our approach is coating the pellets with designed thermochromic inks and making the filament using DIY level filament extruders

Applying interactively changing colors

Many HCI projects have applied interactively changeable colors with photochromic or thermochromic materials, where color instantly changes in response to UV light or temperature. As they do not take up volume, they have been used in thin film-based interfaces [11, 12, 32], textiles [3], or as coating [9, 21, 23].

Beyond aesthetic or design purposes, several projects have used color changes to visualize information. Photochromic carpet uses UV LED embedded shoes to display user footage [24]. Inkantatory paper displays a touched state by changing color changes with thermochromic ink [29]. Our work utilizes thermochromic inks to indicate malleable states during 3D pen tasks.

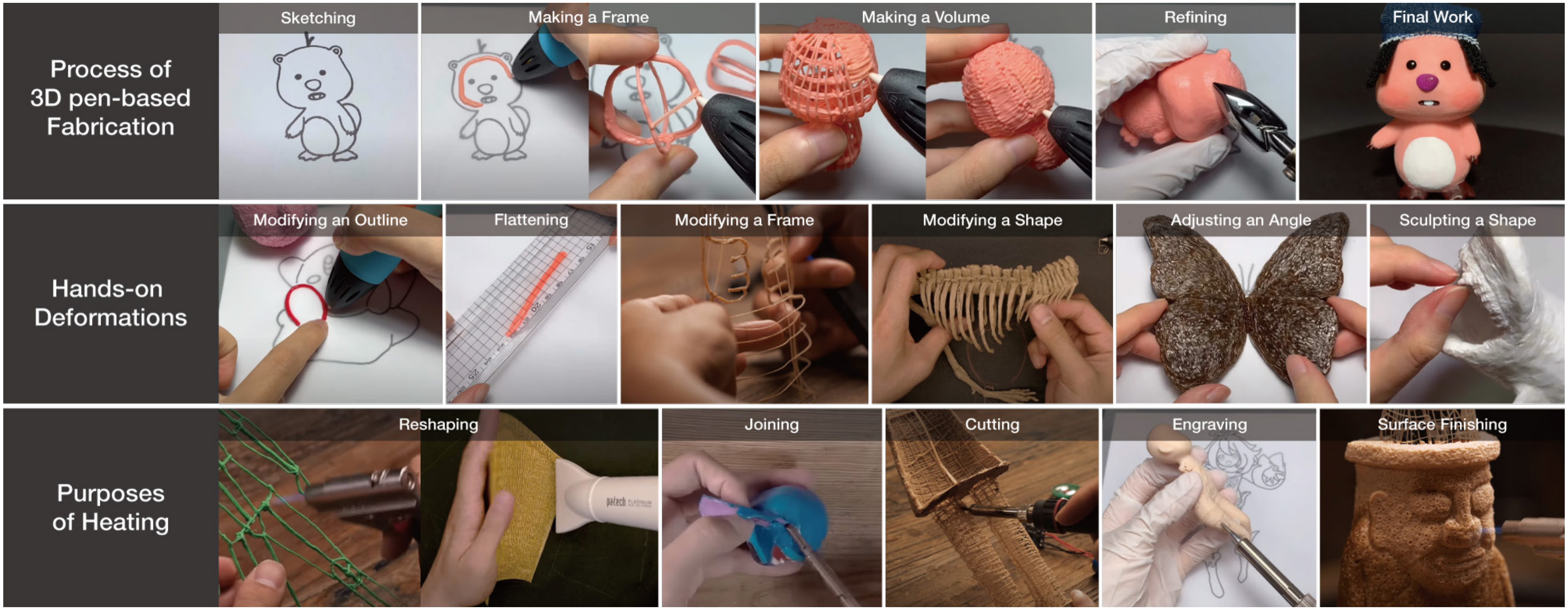
Toward Active Thermoforming in 3D Printing

Unlike 3D pen tasks, heating and modifying 3D printed objects is relatively difficult because most printed objects are made of bulk materials with an arbitrary thickness. Therefore, surface finishing is partly applied.

Several researchers investigated engaging hands-on crafting in digital fabrication while adding the values of hands-on crafting [16, 28, 33, 38]. HotFlex embeds heating elements into the local part of 3D-printed objects for customizing them. Depending on structural patterns, the printed objects can be diversely modified [7]. Instead of embedding heating elements, HeatMat explores the effects of infill structures on heating 3D printed objects to support thermoforming [13]. Ko et al. proposed a metamaterial structure, TF-Cells, to enrich post-print modifications by local and deep heating [14]. Our approach is compatible with desktop Fused Filament Fabrication 3D printer, and might complement the existing approaches by supporting user heating and deformation in desired malleable states.

CURRENT 3D PEN-BASED FABRICATION

3D pens-based fabrication is not only for making a high-fidelity object, but also for doodling while developing an idea, which might come from hands-on crafting [16, 28, 38]. We identified a unique 3D pen process focusing on hands-on deformation and issues with misidentifying malleable states from 38 3D pen-based projects on YouTube.



Process of 3D Pen-Based Fabrication

3D pen-based fabrication consists of four stages.

1. Sketching Users prepare guidance for printing. They bring target objects, print stencils, or draw planar figures.

2. Making a Frame Users print 2D frames following the sketch and join them to a 3D frame. Some users vertically extrude from a 2D frame to build a 3D frame. When printing, they modify the curvature or flatten outlines. Moreover, when making a 3D frame, they deform the vertical structures to keep them from collapsing.

3. Making a Volume Users fill the frames to generate planes. Next, they stack the mass for thickening or making a specific shape. They also join multiple solid parts into a target object. Users repetitively modify the undesirable shapes by hand. Sometimes, they even sculpt the prints to target shapes or express details.

4. Refining Users refine surfaces or add details. They heat and rub or sand surfaces with laminated textures until smooth. Moreover, users embed some patterns, and color surfaces.

Heating in 3D Pen Tasks

Heating is a method of controlling the malleable states of printed parts, which occurs mainly in making a volume and refining stages. Lighters, heat guns, and soldering irons are frequently utilized. We have illustrated the purposes of heating. First, users locally heat to reshape the frames or objects. They first heat the target parts, and then join multiple parts or cut a local part. They engrave surfaces with a soldering iron for embedding textures or other parts. Finally, heating is applied to the surface finishing to make it smooth and glossy.

*All images in this page are from 3D SANAGO, and Haebokka channels after getting permissions

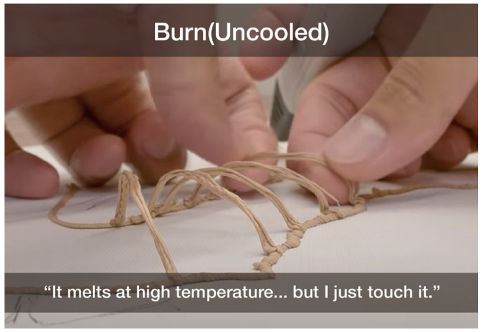
3D SANAGO: https://www.youtube.com/c/%EC%82%AC%EB%82%98%EA%B3%A0/
Haebokka: https://www.youtube.com/c/%ED%95%B4%EB%B3%B4%EA%B9%8CHaebokka/

Issues from Misidentifying Malleable States

Even expert users often made mistakes, which are caused by misidentifying the malleable states.

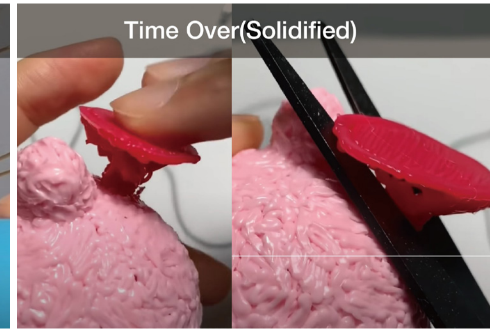
Issues about Solidifying

Issue 1. When a user detached the uncooled printed parts, the stencil paper was stuck to the printed parts. He said, "You should detach it after it is definitely cooled."



Issue 2. Users could be burnt from hot mass when they touch the freshly extruded or heated parts. However, some users just deform the hot parts for a quicker deformation.

Issue 3. When extruding mass along the z-axis (in the air), users need to sustain it until solidified unless it falls down.



Issue 4. Users can only deform the parts until they cool down. It is hard to estimate the working time, and therefore, users occasionally fail to modify target parts entirely.

Issues Caused by Heating

Issue 5. When a user heated the surface and accidentally touched it, the hot surface stuck to her finger.

Issue 6. When users overly heat the target objects, the object's surface could be burnt.

Issue 7. When users overly heat the target parts, they may melt.

Issue 8. When users insufficiently heat the target parts, they force them to deform. In the worst case, the target parts may break down.

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3D SANAGO: https://www.youtube.com/c/%EC%82%AC%EB%82%98%EA%B3%A0/
Haebokka: https://www.youtube.com/c/%ED%95%B4%EB%B3%B4%EA%B9%8CHaebokka/

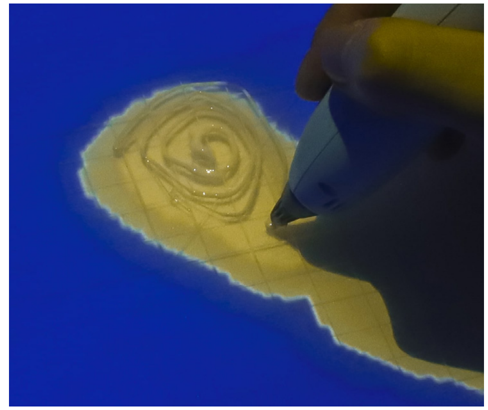
EXPLORATION OF DESIGN CANDIDATES

We built three pilot interfaces to explore ways of displaying malleable states and evaluated them in terms of visibility, usability and technical feasibility.

Highlighting Glossiness

Our first attempt was to illuminate the extruded parts. By controlling the angle and intensity of the light, we assumed that gloss could be perceived well regardless of the ambient light. We attached a mini handheld light to the 3D pen. Then, we extruded the filament while controlling the intensity and angle of the light.

The identification of visual cues remain ambiguous. In addition, controlling the intensity and angle of the light interferes with the 3D pen's tasks.



Visualizing Temperatures by Projection

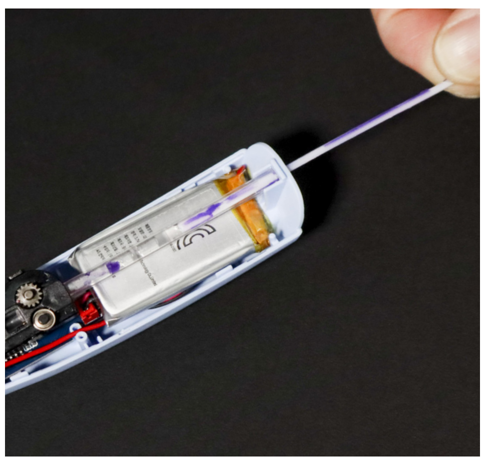
We developed a simple interface that senses the temperature of an extruded mass and visualizes it by projection. This did not require any manipulation. Because contact sensors can deform the malleable mess, we used an IR camera (FLDR) to measure temperature.

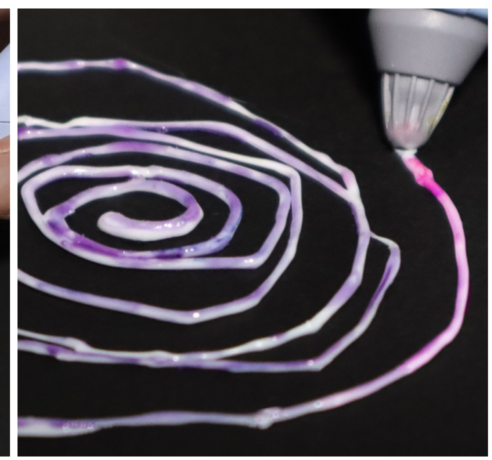
Unfortunately, the extruded lines from the 3D pen are too thin for the IR camera to capture the target points. The camera barely senses the temperature of a nearby spot, that is, a broad circular area.

Coating Filaments with Thermochromic Ink

Our final trial was to coat the existing 3D filaments with a thermochromic ink. We brought a commercial thermochromic ink, in which purple ink turns pink at 60 ^{o}C and immersed the white PCL filaments in the ink for an hour and dried for 24 hours at around 24 ^{o}C. As seen in the left most figure below, the thermochromic ink tightly combined with the fialment. However, the coated filament was not possible to extrude through the 3D pen. As seen in second figure, the coated filament was clogged at the middle of the channel as the thickness of the filaments increased.

Next, to quickly test the feasibility of thermochromic ink, we directly applied the ink while printing the spiral line. Once the ink was applied, the colors instantly changed. As the color change was apparent, we could easily guess the temperature, as illustrated in the right most figure. Since coating commercialized 3D filaments was not applicable, we rather chose to develop a 3D printable thermochromic filament.



DESIGN OF THERMOCHROMIC COLORS

Thermochromic ink is a type of dye that changes colors with temperature changes. It is possible to customize thermochromic inks by combining different CMYK pigments with target temperatures. To specify the colors and target temperatures, we held a design workshop.

Design Workshop

A design workshop has three main goals: to identify the stages of perceived malleable states during 3D pen-tasks, to develop rationales for color combinations, and to provide insight into the design of thermochromic colors.

We recruited six UX and interaction designers who had experience with 3D pen tasks. We paired two designers in a group to derive their discussions.(Group A: D1,D2; Group B: D3, D4; and Group C: D5, D6). We used normal CMYK inks instead of thermochromic ink and highlighted them to avoid making the colors too complicated for technical feasibility.

Workshop Configurations The design workshop consists of three sessions followed by a semi-structured interview. Each workshop was conducted for two and a half to three hours.

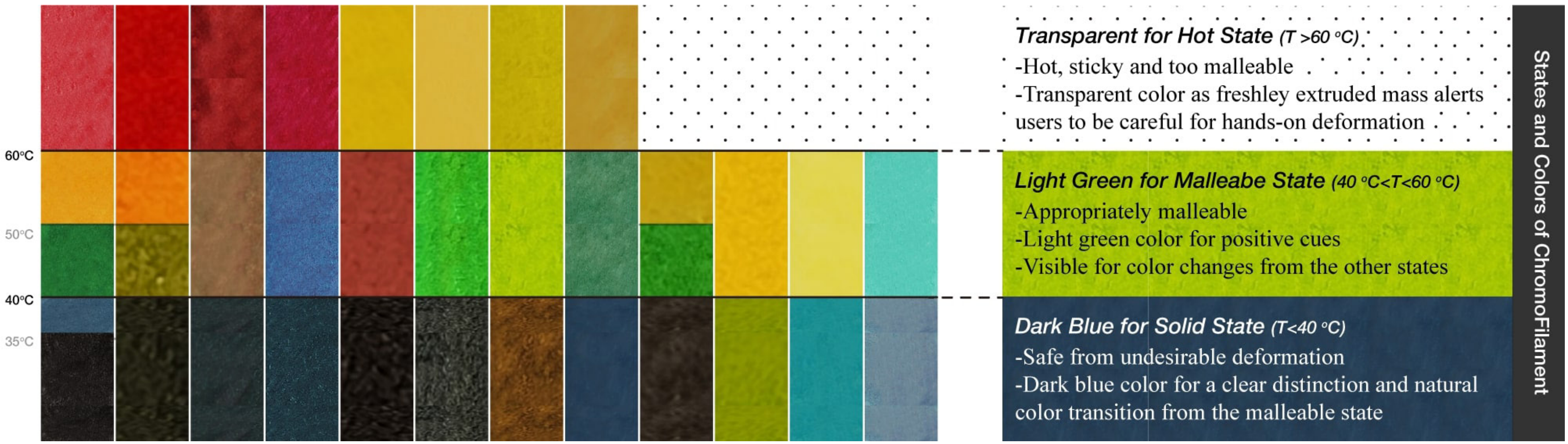
First, the designers experienced the malleability of filaments using 3D pens or heating in 70 °C water. They deformed the heated material while checking temperatures with thermal cameras. Then, they distinguished the degree of malleable states.

In the group design session, the designers designed colors for each malleable state based on the group discussion. Considering the complexity, we asked them to repeat the design at least twice, which included the selection of the malleable states.

In individual design sessions, designers individually designed the colors and the malleable sections again and commented on each other's designed colors.

Results of Design Workshop

We derived design the considerations and specified the colors and states of ChromoFilaments.



Perception of Levels of Malleability

Hot state If the temperature is above 60 °C, designers thought that the extruded mass is melted down and will burn the users.

Malleable state If the temperature is between 40 and 60 °C, designers believe the state is reasonably malleable. In the first trial, Groups A and C divided temperature range into two sections: from 40 to 50 °C, and from 50 to 60 °C. They thought that the range from 50 to 60 °C was suitable for the deformation of an overall shape while the range from 40 to 50 °C was suitable for more limited deformation, such as local bending or twist.

Solid state The designers chose temperatures less than 40 °C as the non-malleable range. Although materials were slightly deformable at 35 °C, they chose the assured deformable range.

Design Considerations for Color Combinations

Intuitive colors that match each state Designers used warm colors or transparent for a hot state, and cool colors for a solid-state. They preferred bright colors for the malleable state. They were worried about using bright colors for a hot state so as to not provoke the users' touch. D1 said, "Bright yellow would tempt users to touch it."

Clear color distinction between states Designers tried to give distinctive colors between states. They changed the transparency or hues from a malleable state to a hot state to clearly alert users. Similarly, many of them chose extremely dark colors or highly altered hues for the non-malleable section.

Reducing the complexity of color combinations Designers preferred a small number of colors so as to not confuse users. After several iterations, Groups A and C integrated malleable sections to reduce colors.

Color Selection Process for ChromoFilament

Referring to the color combinations, we selected ChromoFilament's colors for each state. Note that this is one example.

Select level of states Considering novice users, we selected the minimum number of states: hot state(>60 °C), malleable state (bewteen 60 °C and 40 °C), and solid state(<40 °C).

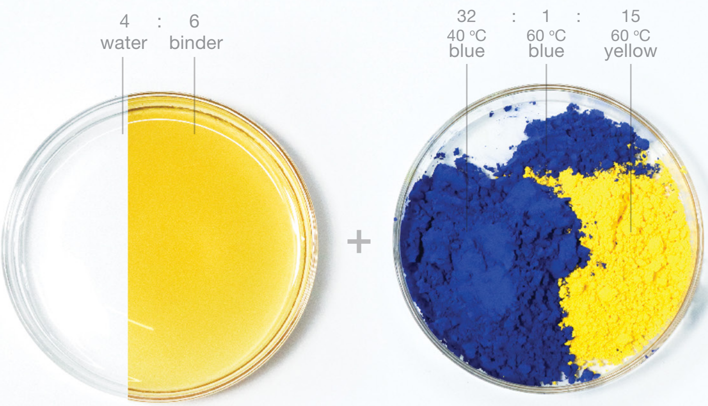
Hot state We started from choosing the color of the hot state as it is easier to consider overall color combinations. While red and yellow are also recommendable, transparent color makes other states' color options flexible.

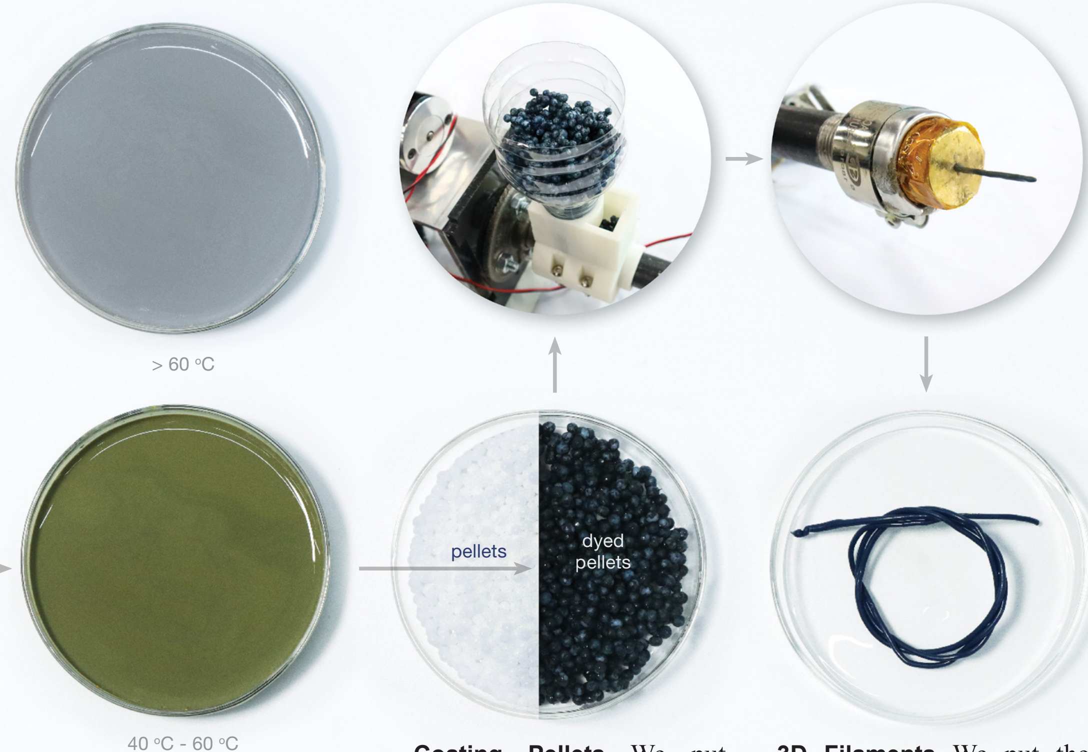
Malleable state Next, we used light green color for the malleable state. To provide positive cues, we tried to make it bright. Moreover, users can clearly perceive their color change from other states. Yellow or bright cyan were the other options.

Solid state Finally, we used dark blue for the solid state. We tried to make it dark for a clear distinction and intuitiveness. Black and browns were the other options.

IMPLEMENTATION OF CHROMOFILAMENT

To embed the designed properties into 3D filaments, we combined the thermochromic pigments and filament material and extruded them into a filament form. We chose to coat pellet materials with thermochromic ink rather than dissolved pigments into the molten material. This is a simple and feasible way to control pigments' concentration in DIY scale fabrication.





Binders We made a mixture of water and a commercialized watercolor binder*. A higher volume ratio of the binder makes the ink too viscous and increases the thickness of the applied layer. In contrast, if the binder ratio is too low, the coating thickness becomes too thin and it hardly adheres to the target surface.

Colors Contrary to theory, thermochromic pigments do not become completely transparent, but only translucent. It makes colors darker at a higher temperature. To make a bright green, we used a large portion of yellow pigments, which became transparent at 60 °C (60 °C yellow), compared to 60 °C blue.

Coating Pellets We put 100g PCL pellets* (3mm diameter) and the 30ml thermochromic ink into a zipper bag, and mixed them. Then, we dried them for 24 h with a fan at room temperature (~ 24 °C). The diameter of coated pellets is 3.31 mm (S.D: 0.14, from 20 samples).

3D Filaments We put the coated pellets into the DIY level filament extruder**. We set the extruder's temperature to 55 °C. Finally, we extruded filaments from the extruder, which have a uniform 1.75mm thickness.

*Mijello Mission Gold Watercolor Binder(WM-500): http://mijello.com/83
**FILASTRUDER(299.99$): https://www.filastruder.com/

CHROMOFILAMENT-BASED 3D FABRICATION

ChromoFilaments display malleable states when printed parts are extruded or heated as shown in the figure below. To explore the detailed effects of ChromoFilament on the fabrication process and behaviors we observed users working with ChromoFilaments.

We recruited six people who have experience in 3D fabrications. We provided stencils for a 3D bunny and 3D pens with ChromoFilaments. Moreover, typical hand tools and heat guns were given. During the fabrications, we asked participants to think aloud protocol. We video and audio recorded the entiree experiment.

As some participants had no experience with a 3D pen, we showed an example video of making a cone-shaped carrot with a 3D pen, and introduced them to a way to use a 3D pen and a heat gun. Then, we asked them to fabricate a simple 3D cone with normal filaments in 10 minutes.

The main task was to freely fabricate a 3D bunny— Easter Bunny*—with the ChromoFilament by referring to the stencil,. The bunny is selected because it consists of mul- tiple parts with organic geometries.

Among the participants, we illustrated P6's fabrication process in detail on the next page, which well exhibits users' distinctive behaviors with ChromoFilaments (F1-F16).

Perceiving Malleable State through ChromoFilament

As we did not provide any information on ChromoFilament, participants were surprised by the color changes when they first extruded the ChromoFilaments. They explored their colors and malleable states by touching them. After feeling them, all participants were able to identify the states by observations. P4 said "I think it is intuitive. I naturally think dark blue is stiff. Also, it was obvious that the transparent gray is hot and sticky. Finally, yellow green indicates that it is okay to touch the material."

Moreover, as intended, they were able to perceive the printed parts' color changes during fabrication. It is distinctive from the tutorial session where participants repeatedly touched the extruded parts or carefully paid attention to the printed parts to prohibit their fall.

Making Multiple Frames until Fully Cooled

In making a frame stage, we could often observe that the participants waited for a moment when the color of the extruded part turned green, and then deformed it as P6 did in Figure F3. Moreover, when detaching the frame from the mat, they waited until the frame became dark blue. For these behaviors, we did not observe mistakes from participants, such as hot mass sticking around, or structural collapse.

While waiting for a target part to harden, participants tried to print other frames, as illustrated in Figure F2. They planned for the overall printing flow depending on the size of the target part. For example, P6 printed body contour first and then decided to print legs rather than small arms (F2). He said "I realized that my body takes more time to cool down. So, I made the legs and arms in parallel."

Identifying the Printing History with Colors

ChromoFilament allows users to track their printing pat by the color changes. When making a volume, users first filled the 3D frames, as in Figure F4. Then, they stacked the filament to create a volumetric shape (F5).

This stage is repetitive and tidy, with users often missing their way and thus extruding mass from malleable parts, resulting in unwanted deformations.

With ChromoFilament, participants prevent this problem. As illustrated in Figure F5, P6 adjusted the printing path to avoid the parts in a hot state. Regarding this, P5 said, "It is similar to watercolor paint. I tried not to do any additional work unless the color turns blue."

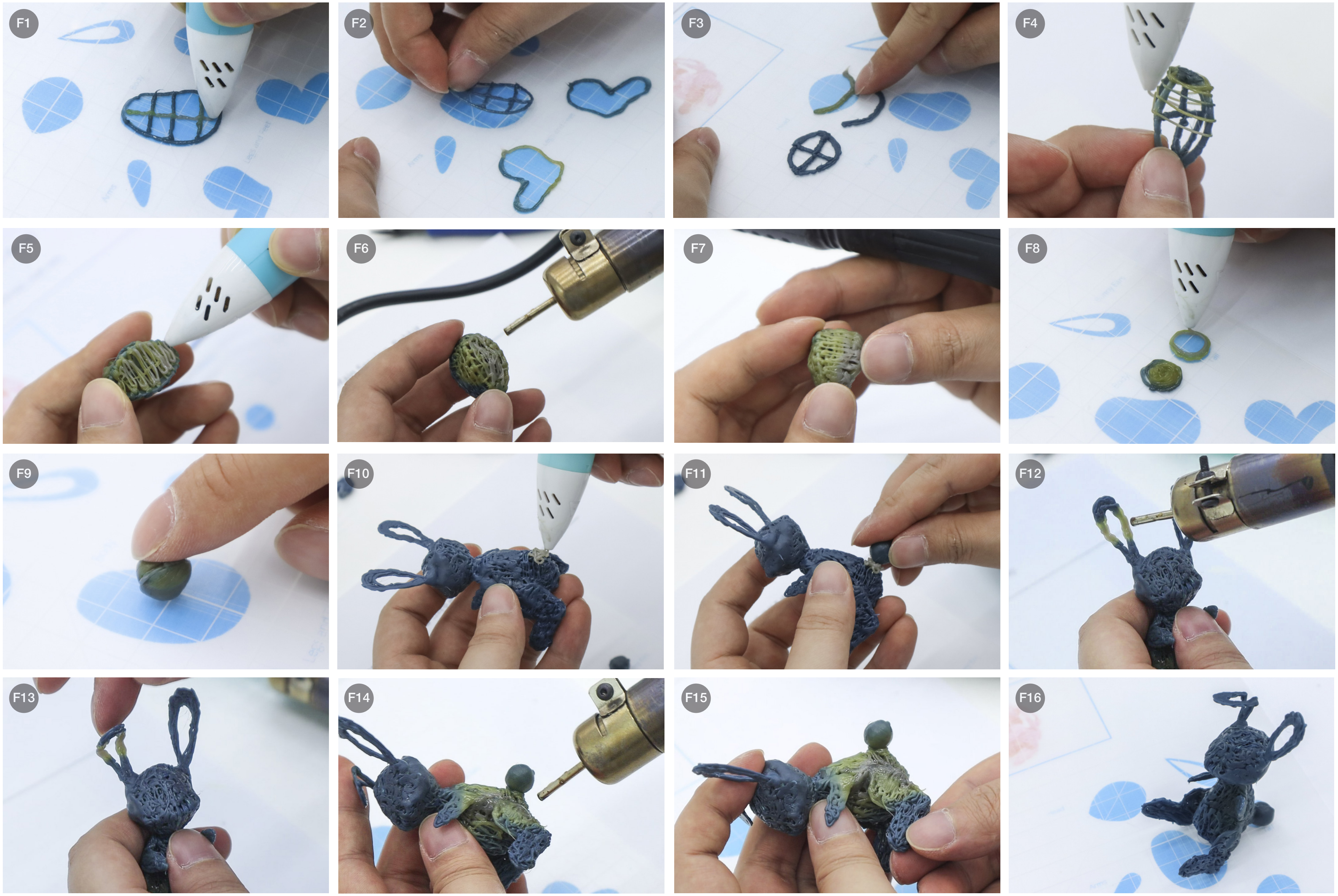
Fabricating with Explicit Working Time

By observing the color of ChromoFilaments, users can identify the remaining time for deformation in real-time. Regarding this, P2 said, "It is like a Pomodoro timer." Explicitly checking the working time allowed users to continuously deform without the anxiety of Time Over.

Further, users can take different actions according to the remaining time or stage of fabrication. P6 planned to sculpt the tail of the bunny using bulk mass. To print bulk mass, he printed overlapping spirals (F8). As the freshly extruded mass heat overlapped parts, the working time was prolonged. Therefore, he could keep them deformable until printing enough mass. Next, when sculpting, he deformed the part with light blue first as it would have solidified earlier than the green colored parts (F9).

When joining multiple parts, users often used hot mass such as hot glue (F10-F11). Similarly, depending on colors, users can choose to quickly join, extrude hot mass again, or heat up.

*Easter Bunny: https://learn.the3doodler.com/stencils/easter-bunny/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ChromoFilament in Heating

Compared to extrusion, the heating of printed parts is more difficult. Users should visually identify the states from glossiness or melting down movements, which could lead to fabrication failure. In addition, local heating with a lighter or heat gun is very hard where ambient thin parts can be melted down. Indeed, we let participants heat their 3D cones, and P2, P3, P4, and P5 failed to control heating. In this regard, ChromoFilament effectively aids in heating. As they identify the malleable states of the target parts with colors, each participant successfully heats the 3D cone according to their purpose. Moreover, they started to heat actively without much concern for safety issues or fear of failure.

Selectively Heating toward a Desirable Malleable State

When heating ChromoFilament, the color of the heated part instantly changes to green. Participants easily distinguish between heated and unheated parts including their states. P1 said, "Wow, very interesting! Looks like a heat simulation!"

First, users can control the degree of heating, i.e., the level of the malleable state, according to the deformation plan. For example, P6 heated the overall shape of the bunny's head to reshape it (F6). Interestingly, P6 heated the jaw part until the hot state for an in-depth deformation while slightly deforming the other parts (F7).

Second, users can confine the deformable parts. For example, P6 heated only the local area until it turned slightly transparent green (F12). Then, he repetitively bent the bunny's ear while holding the non-malleable part which prevented undesirable deformations (F13).

Finally, users can safely heat the target to a desirable malleable state. When adjusting the leg angle, participants deeply heated the parts near the leg joint (F14). As the heating time increased, some parts were in a hot state. We found that participants paused heating until the overheated parts turned green, and then carefully heated it again as P6 did in F15

DISCUSSION

Practicing 3D pen-based Fabrication with ChromoFilament

ChromoFilament is a great tool for learning 3D pen-based fabrication. It displays educational information. Because a ChromoFilament displays three states, users always considered that there were at least three states. This allowed them to naturally investigate each state. Ways of heating should be adjusted according to the thickness of target parts, heating tools, or even room temperature. Users can practice the way of heating or even simulate heating tools by observing the color changes of ChromoFilament. Similarly, as P6 did, users can systematically get a sense of the working time by varying the volume of extruded parts, geometry, or extruding path.

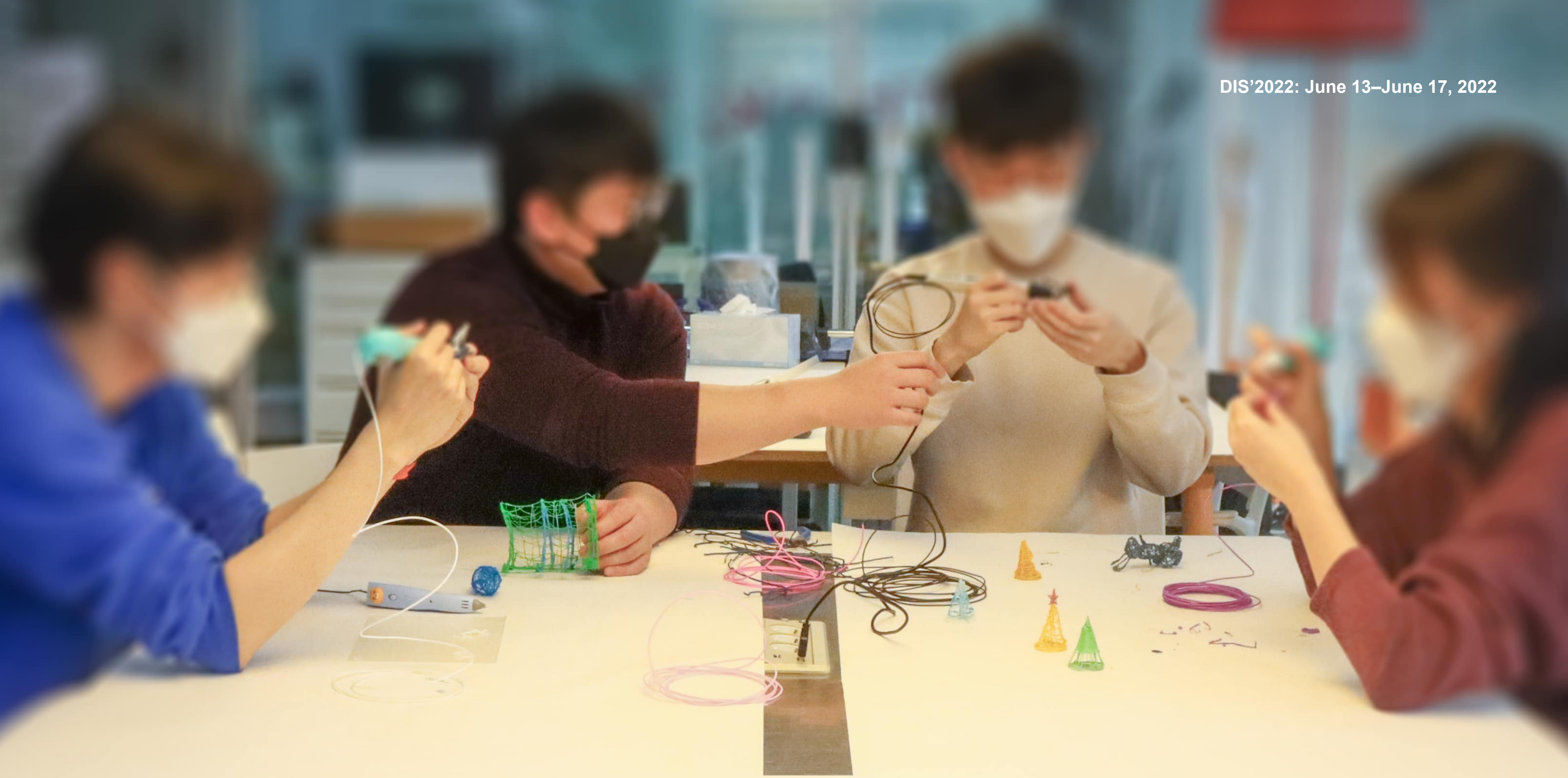
Deforming the extruded parts and heating them are essential but risky as they can destroy the parts. However, with ChromoFilament, users can maintain a safety line. For example, when deforming, users would at least wait until target parts became green-colored. Even if they overheat the parts, they can instantly pause heating to fabrication failures or burns. Thus, users can safely fabricate 3D objects through trial and error

Customizing 3D Filaments for Various Purposes

The participants exploited three states of ChromoFilament for different purposes. Once users get used to the colors, visualizing more diversified stages might not be complicated. In this sense, customizing stages of ChromoFilament can deliver specific and personalized information.

Our approach can be applied to existing HCI approaches. It can complement structural approaches for thermoforming by guiding users' manual deformation and heating [7, 13, 14]. Similarly, in 4D printing contexts, the designed filament can visually guide heating steps or indicate its self-deformed history as it needs to be heated up between melting temperature and glass temperature [2, 30].

Moreover, the customization of the filaments' functions can vary with different powders (or powder mixtures). For example, it enriches the design space of using a 3D printer and 3D pen together [26]. Also, by applying irreversible thermochromic pigments or photochromic pigments, users can directly print functional objects where their colors change depending on temperature or UV light, rather than coat after printing objects [9, 21, 23]. Finally, with a magnetic powder or iron powder, fabricating actuatable objects might also be applicable.



LIMITATION AND FUTURE WORK

Reversible thermochromic pigments with high target temperatures (>80 °C) are not widely commercialized. However, as PLA becomes soft around 60 °C, ChromoFilament can still be applied to PLA in thermoforming contexts, or 4D printing contexts [2, 30]. Next, our approach is based on physically mixing powders and plastic in a molten state, which is similar to compounding. Although users did not feel a significant change in the filament while using ChromoFilament, its properties may differ because of the compounding process. It would be beneficial to explore the effects of blending functional powders on mechanical properties.

CONCLUSION

In this paper, we presented the overall design process for ChromoFilament and users’ fabrication with it. We have highlighted the typical process of 3D pen-based fabrication and problems caused by a misidentification of the malleable states. We investigated to designing the filament with thermochromic properties to relieve this problem. Based on the design considerations from design workshops, we designed ChromoFilament and fabricated it using DIY processes. Finally, we illustrated the fabrication and user behaviors of using ChromoFilment. We believe our approach and findings can not only inspire ways of supporting creativity through thermoforming but also promote heat-based processing in 3D printing.

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