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Xpandables: Single-filament Multi-property 3D Printing by Programmable Foaming

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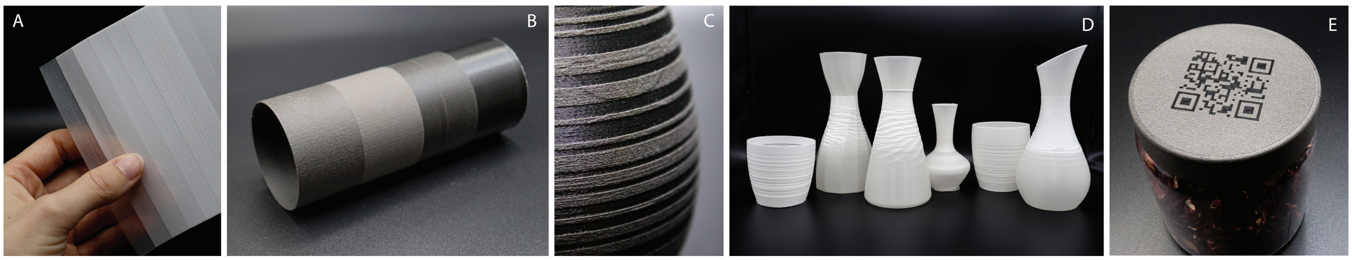

Figure 1: Examples of color and texture variations using a single foaming filament. A) Varying translucency. B) Color variations in a black filament. C) Barcode application using a color contrast. D) Grip texture examples. E) An embedded QR code.

ABSTRACT

We propose a new approach to obtain local property variations in 3D-printed objects using a single-nozzle 3D printer and one filament. We use foaming filaments which expand at different rates due to different temperatures. We present an approach to harness this varying expansion by including parameters of the 3D printing process in the design space. This makes the foaming programmable and allows for achieving a wide variety of properties from a single material. We show how objects with locally varying shade, translucency, gloss, and texture can be fabricated. Our approach turns single-nozzle 3D printers into more versatile systems while eliminating the challenges of multi-material 3D printing. This is in contrast to the drive towards an increasing number of printable materials and more complex 3D printers. We demonstrate the capability of our approach by 3D printing objects with embedded barcodes, QR codes, and varying tactile properties.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**.

KEYWORDS

3D printing, personal fabrication, foaming filaments, digital fabrication

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1 INTRODUCTION

Multi-material 3D printing can enable new functionalities and material experiences in products. It allows fabricating complex products with locally varying properties and functionalities using a single fabrication process [5, 11, 14]. Among the 3D printing technologies, fused deposition modeling (FDM) is one of the most widespread printing technologies, mainly due to its affordability and accessibility to everyday users.

However, because of the semi-continuous extrusion process, FDM, even when equipped with multiple nozzles, is generally limited to a small set of materials per part, where each material can only be assigned to a discrete volume. Fabricating parts with local variations within a palette of properties is, therefore, not trivial. Other multi-material solutions for FDM require significant hardware changes or additions, such as a mixing nozzle [2]. Furthermore, combining chemically different materials poses challenges to the printing process [7, 11]. Also, the bonding quality between different materials is highly dependent on printing process parameters, which have to be determined for a given material pair [3, 30, 34].

Within the HCI community, there has been a constant drive to expand the capabilities of 3D printing technologies. This includes new workflows for multi-material 3D printing [20, 29], using existing 3D printing processes in novel ways to allow new interactions [10, 23], combining 3D printing with textiles [27], and applying reversible color to 3D-printed parts [26]. The multi-material capabilities have been used, for example, to embed data using infrared tags [9] or to fabricate objects with pneumatic controls [32].

We argue that using multiple materials is a means to achieve multiple properties and not a goal in itself. Complementing the current drive for an increasing number of base materials, we propose an approach that uses one single filament which is programmed during the 3D printing process to result in parts with multiple properties. In this case, we use a commercially available foaming PLA filament as the base material. Foaming filaments have a foaming agent that releases an expanding gas during extrusion through the printing nozzle, which creates a foam with a closed-cell structure [1]. The amount of expansion can be controlled by the printing temperature. We harness this response of the material to the printing process by using the printing process parameters to program the final properties of the material. We demonstrate how this method can be used to fabricate multi-property results with locally varying color, texture, and translucency. Our approach turns single-nozzle 3D printers into more versatile systems while eliminating the challenges of chemical and process incompatibility of multi-material 3D printing.

Our main contributions are:

- Introducing a new approach to achieving locally varying properties in a part using single-extrusion 3D printers
- Presenting an accessible alternative to multi-material printing
- Demonstrating interactive products fabricated with our approach

2 RELATED WORK

2.1 Multi-Material Printing with FDM

There are different approaches to fabricating multi-material parts with FDM. With a standard single-nozzle FDM printer, it is possible to pause mid-print and manually insert another material into the fabricated part [18]. This *print-pause-print* approach requires significant manual intervention. Automating the material-switching process is the method of Programmable filament [29]. In their approach, a filament is pre-fabricated and composed of different material segments. Each programmable filament is custom-made specifically for the object to be printed. Commercial add-ons also exist that pre-splice different filaments into one thread, so that multi-material parts can be fabricated using one single nozzle[1].

Some of the FDM printers on the market are equipped with multiple nozzles. As the printer then needs to switch between the materials continuously, the applications are generally limited to parts where one material is assigned to a discrete region of the part. For example, it is not trivial to assign a region in which specific ratios of the two materials are applied. Multi-nozzle printing also limits the material combinations that can be used, as not all combinations are compatible. Bonding between two materials can be improved by an interlocking structure [16].

A different approach to multi-material FDM printing is a mixing nozzle where multiple filaments are fed into a single nozzle, and their feed rate is adjusted according to the desired material composition [2, 12]. This approach allows functionally graded parts by mixing materials in the melt chamber with varying feed rates. However, it requires specialized hardware, different from the extrusion systems found on common FDM printers.

[1]https://www.mosaicmfg.com/products/palette-3-pro

2.2 Foaming Materials

Recently, a new category of materials for FDM 3D printing has become available. These are filaments that are saturated with foaming agents [15, 22] and expand into a foam while printing. The expansion occurs due to the activation of the foaming agent by the printing temperature and the sudden pressure drop after the printing nozzle. The characteristics and resultant material properties of the 3D printed foam are highly affected by 3D printing process parameters. The influence of parameters such as nozzle temperature, cooling, material flow, and print speed on foam microstructure and density of the printed material has been investigated. Some of the prior work aimed at tailoring the mechanical properties of the 3D printed foam [6, 8, 15, 25], while others presented continuous hierarchical structures by controlling the foam microstructure [19, 21, 31].

Most existing applications of foaming filaments employ their lightweight properties [13, 17, 28]. Medical applications demonstrated the use of the porous structure of the PLA foam as a bone simulant for surgical training [33] and as a medical scaffold [4]. There are also a few applications that utilize the varying density of foaming TPU for custom crutch grips [24] and hardness for soft pneumatic actuators with variable stiffness [8].

3 OVERVIEW OF XPANDABLES

The significance of our approach is using a single filament to achieve a multi-property result, leveraging the response of the filament to the printing process. We utilize the property changes of the foaming material at different expansion rates by varying the process parameters during 3D printing. This allows us to vary the properties within a printed object locally. Using the locally varying properties, or using the contrast between them, we define a design space.

The foaming filaments we use can be extruded in an unfoamed state at lower temperatures. With higher temperatures, the foaming agent inside creates voids, and the material expands. The amount of the expansion is mainly temperature-dependent, but other process parameters are also affecting it.

Contrary to a conventional FDM printing workflow, where process parameters are set during the slicing step to optimize printability and part quality, we include the process parameters in the design space. Since the process parameters can be programmed and varied within a range of possible values, we consider the foaming of the filament to be programmable in our approach. For the entry-level design pipeline, users need to split their 3D design into multiple bodies, each corresponding to a desired property. Slicing software is then used to assign the different process parameters to each part according to the desired material properties. This is an accessible workflow for everyday users where standard CAD and slicing software are sufficient to obtain local property variations within the design. The design pipeline that offers more fine-grained control, such as graded transitions of properties, requires a dedicated script that generates g-code with custom toolpaths and fine-tuned process parameters.

4 DESIGN SPACE

4.1 Materials

Currently, PLA, ASA, and TPU-based foaming filaments are commercially available. This paper discusses our approach on foaming PLA, namely LW-PLA by Colorfabb[2]. However, comparable design space and characterization of foaming apply to other foaming materials similarly.

4.2 Foam expansion rate

The microstructure of the printed foam affects the material properties significantly. By controlling the process conditions, hence the foaming rate, we can obtain a range of properties. A major indicator of foaming is the change in density, or the expansion rate, in comparison to the unfoamed state of the material. Foaming materials exhibit a range of different properties depending on the process temperature. According to our findings, the density of LW-PLA ranges from 0.51 g/cm^3 to 1.24 g/cm^3, between the unfoamed and maximum foamed states.

4.3 Visual and tactile properties

4.3.1 Color. A visual effect of foaming is the color shade change of the material. We show how the changes in color are related to the expansion rate; with an increasing expansion rate, the printed material appears lighter. Figure 2 shows the color variation of a black filament at different expansion rates. The color of the printed part ranges from black in the unfoamed state to light gray, the color at the highest expansion rate. A similar variation happens with different color filaments; however, the highest apparent contrast was achieved with black filament. Here, we show the color changes at steps of 5°C nozzle temperature; a finer color gradient can be achieved with smaller steps.

4.3.2 Translucency. The translucency of the printed part varies at different expansion rates. This is most evident with the white color filament. The sample in Figure 3 shows a translucency gradient created with an increasing nozzle temperature. While the unfoamed state is translucent, the highest expansion rate produces a distinctly more opaque material.

4.3.3 Texture. The expansion rate has an effect on the printed surface's texture as it creates variations in surface roughness. The differences in surface roughness can be observed in Figure 2. We found noticeable visual and tactile changes, such as softness, warmth, and reflectivity, within an 80°C interval of nozzle temperatures. The material feels softer and warmer as the expansion rate increases while the reflectivity reduces significantly. The difference can be seen more clearly by comparing the unfoamed sample at 205°C with the highly foamed sample at 205°C.

An interesting effect of foaming is on the visibility of the layers. The layer lines become less evident with increasing nozzle temperature.

Apart from the texture change with the expansion rate, we were also able to create bumps on the surface by controlling the flow rate. Using the volume expansion at 100% flow and guiding the expansion in the line width or z-height directions, surface bumps up to 0.2 mm on both vertical and horizontal surfaces were achieved. Higher bumps can be achieved on vertical surfaces by modifying the print path and on horizontal surfaces by increasing the flow rate and z-height.

[2]https://colorfabb.com/lw-pla-black

5 CHARACTERIZATION

5.1 Process temperature

The nozzle temperature is the main parameter to influence the heating of the extruded material and, therefore, the expansion. Additional parameters related to heating and cooling are secondary to fine-tuning the extrusion temperature.

Nozzle temperature (NT): The maximum temperature the material reaches during the extrusion process defines the state of the printed material. The primary heat source for this is the nozzle. We extruded LW-PLA within an NT range of 190 to 280°C. As seen in Figure 4, at 40 mm/s print speed, the foaming agent starts to act around 210°C, the expansion peaks around 245°C, and from there on there is a decrease in expansion until 280C. In terms of color and density, reaching comparable results on both sides of the peak is possible.

An essential consideration for NT is to minimize temperature changes during printing. One reason for this is the time required to change NT, which is especially important when printing with a single extruder. Large changes in NT are time-consuming and may reduce the print quality due to the cooling of the already printed part. Besides, there is potential material oozing while waiting for the temperature change. Another reason to minimize the NT change range is that large temperature differences between printed regions may affect each other.

Build plate temperature (PT): A heated build plate provides a heated printing environment which is especially significant for the initial layers. Since it affects a layer in its entirety, this is a parameter to account for when setting the NT.

Build chamber temperature (CT): We found that ambient temperature influences the expansion rate. Therefore, it is important to avoid fluctuations in ambient temperature. If available, CT control would improve the accuracy of the results, and it should be taken into account for NT. The 3D printer we used for the experiments did not have CT control, but we performed the experiments at a fixed ambient temperature within an enclosed environment.

Cooling rate (CR): The cooling fans on the print head also affect the expansion rate. Figure 5 compares 100% cooling with no cooling. As seen with the color shift between two images, 100% cooling has a similar effect to reducing NT by 5°C. Changing the CR can be done much faster than changing NT, and there are no side effects, as in the case of NT. Hence, the benefit of using the CR is to reduce the required changes in NT.

5.2 Print speed

Besides the influence of NT, the duration of the material's exposure to heat also affects foaming. Hence, the activation of foaming increases with prolonged exposure to heat. The time of exposure is directly related to the print speed. Figure 4 shows the influence of print speed on expansion rate. As seen in the figure, foaming starts at a lower temperature at low print speed, and the material expands rapidly with increasing temperature. Inversely, we can see a delay in expansion at high print speed. Therefore, alongside NT, print

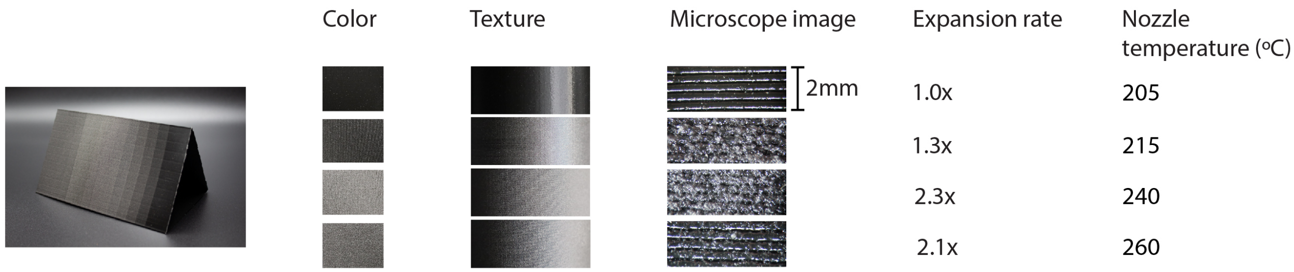

Figure 2: Color and texture at four different expansion rates.

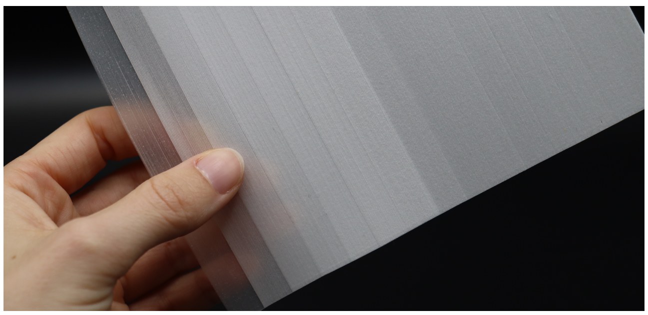

Figure 3: Translucency change at varying expansion rates.

speed is a possible parameter to vary the desired expansion rate. It is important to note that moderate print speeds provide a better gradient of expansion rate and, thus, of the resultant properties at varying NTs.

5.3 Extrusion rate

The changes in expansion rate require control over the amount of extruded material to direct the volume of a printed line. The additional volume of foaming can be used for faster prints by wider extrusion lines or thicker layers. We use this volume expansion to create surface bumps by regulating the flow rate and adjusting the extruded line's width or height.

Line width (LW): LW is the horizontal width of the extruded line. It depends on the nozzle diameter and typically can vary within a small range. The expansion of the material increases the range of LW. We can create bumps on the printed walls by directing the increasing volume in the LW direction. On vertical walls, surface bumps of approximately 0.25 mm were achieved. Higher bumps or inclined surfaces may result in the sagging of the material.

Line height (LH): LH is the z-height difference between the nozzle and printed surface, or in other terms, the layer thickness. LH also has a range dependent on the nozzle diameter. According to our tests, it is possible to extend this range using foaming filaments. With a 0.4 mm nozzle diameter, surface bumps of 0.2 mm were achieved on horizontal surfaces.

Flow rate (FR): The FR adjusts the amount of material extruded through the nozzle. This amount is calculated to fill the space for the given LW and LH along the extrusion move. The adjustment of FR is normally used to compensate for faults in extrusion. However, in this case, since the material expands at the nozzle exit, we need to compensate for the additional volume either by adjusting the FR or LW and LH. To keep the extruded volume constant, we need to reduce the FR according to the expansion rate, such as using a 50% FR for a 2x expansion rate. We can also vary FR locally by controlling LW and LH to create surface bumps. This way, it is possible to create a 3D surface texture.

6 APPLICATIONS

6.1 Using color: QR codes

In this example, we show the capability of obtaining a sufficiently high color contrast via printing parts with a QR code readable by standard mobile phone cameras. Such a way of embedding data on objects may have several uses, such as product personalization, traceability, version control, or sharing product information. Figure 6 shows a use scenario of labeling lids with QR codes. To know more about the jar's content, the user scans the QR code by phone, which then leads to a webpage giving information about the contained herb.

6.2 Using translucency: Barcodes

Similar to the previous example, barcodes can be used to tag everyday objects. Here we demonstrate the possible translucency variation and an example use of it to tag the product with conditionally or temporarily available information. Figure 7 shows a mug with a translucent barcode. The barcode mug reveals the information only when it is filled with a dark liquid.

6.3 Using Texture: Grip

In product design, texture variations are used for several purposes, such as improving the product's appearance or feel, or adding functionality. Xpandables allows for subtle variations in product texture that are more nuanced in look and feel compared to the varying roughness that could be achieved through 3D surface design or slicing settings that are available in most slicers.

Figure 8 exemplifies possible texture variations for grip surfaces. This application utilizes friction of the rough surface of the foamed material, along with the designed texture bumps.

7 DISCUSSION

As the application examples demonstrate, the Xpandables approach provides an accessible method to create interactive objects using

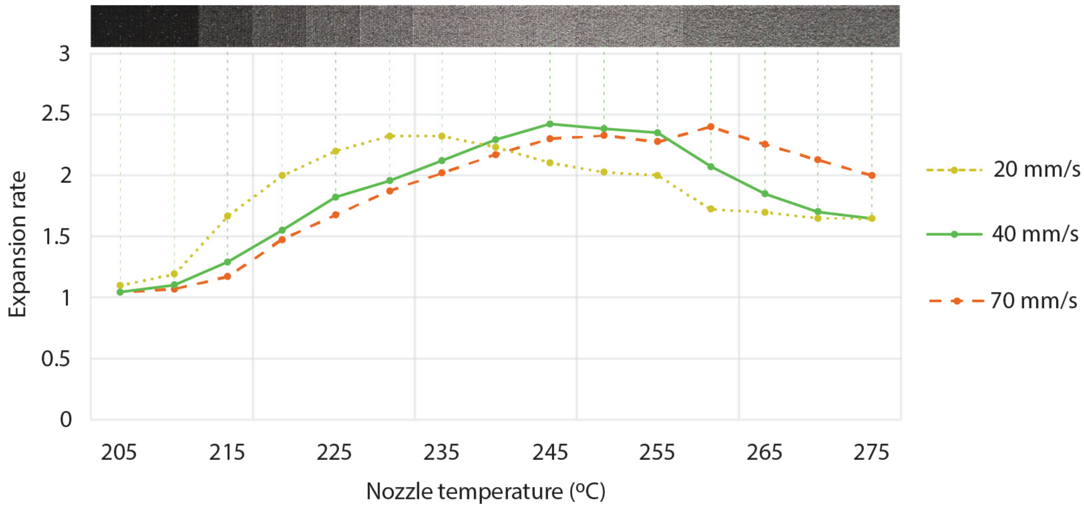

Figure 4: Expansion rate with increasing nozzle temperature at three print speeds. The color gradient on top shows the results at 40 mm/s print speed.

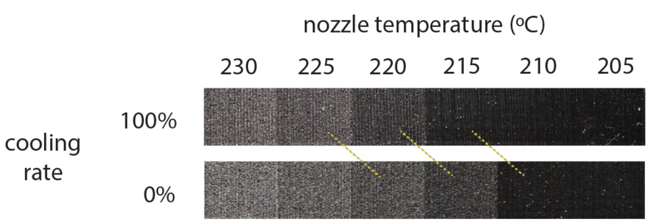

Figure 5: The effect of cooling on expansion rate in terms of nozzle temperature. Dashed yellow lines indicate the delay of foaming with the introduction of cooling.

largely available tools. Furthermore, we allow users to interact with the manufacturing process to use it as a design tool. Besides contributing to the HCI design toolkit, this brings a different perspective on the process, which may trigger further discussions and design opportunities.

In this work, we used one type of filament and fabricated all objects on an Ultimaker 3. While the principles of Xpandables are valid for other FDM printers, some printer-specific fine-tuning is likely necessary.

In our approach, rapidly switching properties between printed layers provides fewer issues than switching within a layer. Strategies for more accurate temperature control can improve the quality of the end results. More optimized printing strategies need to be developed to minimize printing artifacts such as stringing which occurs at travel and waiting time during nozzle temperature changes.

While this paper focuses on visual and tactile properties, we see potential design opportunities for using programmable foaming to achieve variations in mechanical, acoustic, and shape-morphing properties with the same filament. Also, the design space can be expanded by using different foaming materials in combination.

Figure 6: Sufficient color contrast to fabricate readable QR codes A) 3D printed lids with QR codes. B) Scanning the QR code with a mobile phone. C) QR code leads to a webpage sharing information about the herb.

8 CONCLUSION

We present Xpandables, an approach to designing and fabricating objects with local property variations using a single-filament printer. Utilizing the filament's varying expansion, we present the printing process parameters affecting the expansion rate and show how these parameters are used to program local property variations

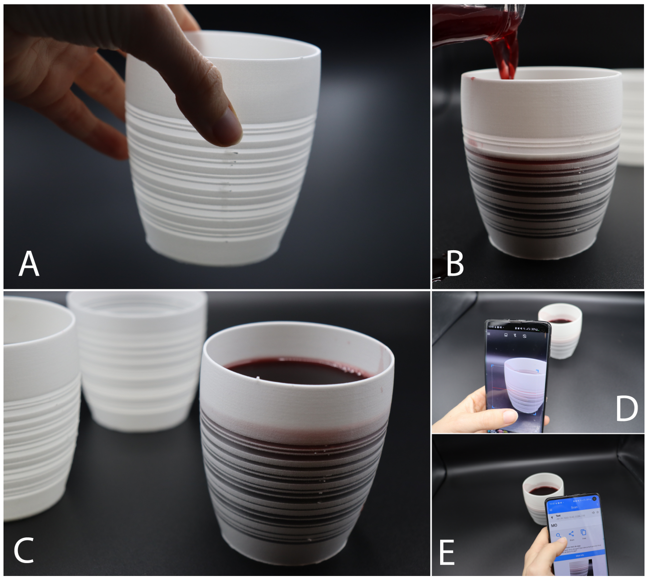

Figure 7: Variable translucency to create conditionally available barcodes A) Barcode mug. B) and C) The barcode becomes readable when filled with a dark liquid. D) Scanning the barcode with a mobile phone. E) Barcode leads to linked information.

in designs. We challenge existing methods where increasing the number of printable *properties* relies on increasing the number of *base materials*.

We demonstrate the capability of our approach to create visual and tactile variations on objects for interaction. With this work, we intend to encourage the HCI community to unlock the responses of filaments to the 3D printing process with the goal of turning conventional 3D printers into more capable systems without introducing issues of complex multi-material 3D printing.

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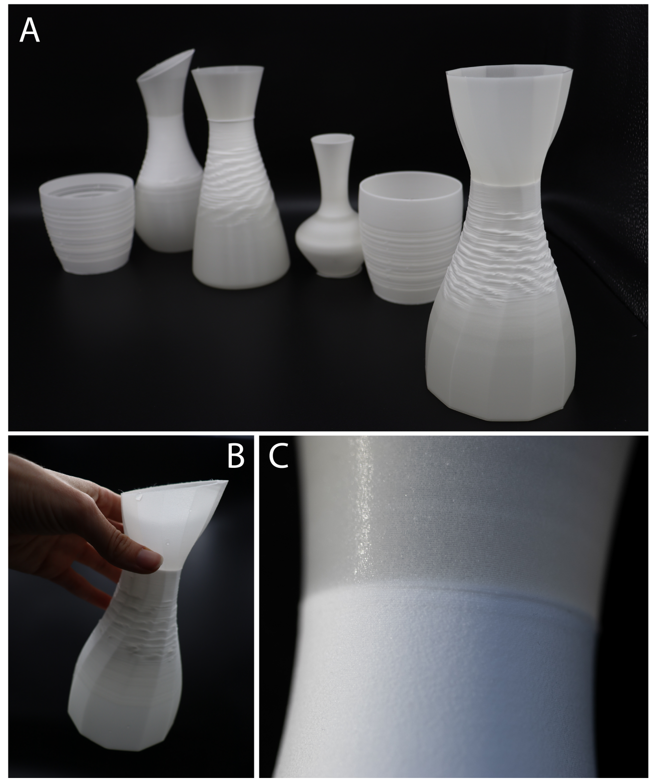

Figure 8: A) Example objects with grip textures. B) Surface texture contrast. C) Surface roughness change on grip surface.

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