# Bake-Ori: 3D-Printed Origami Tessellations for Food Patterning and Folding

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2.s998 Additive Manufacturing

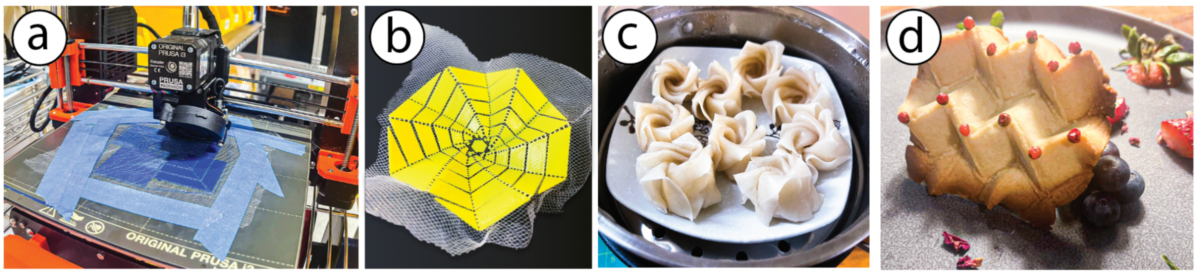

**Figure 1:** Bake-Ori are 3D printed origami tessellation molds used to fold food wrappers and dough sheets. (a) Bake-Ori molds are 3D printed on an FDM/FFF printer on a piece of tulle fabric all in one piece, (b) and are then folded to take their form. (c) Bake-Ori molds can be used to fold dumplings, which are then steamed, and (d) baked as cookies.

## 1. Introduction

The emergence of additive manufacturing, commonly referred to as 3D printing, has gained significant traction across many industries, including the food sector. In the context of food, additive manufacturing has been used in several forms from 3D printing edible filament, like dough and chocolate, to construct three-dimensional structures [1] [2], to creating highly customized and geometrically intricate tooling for cooking. For example, researchers have developed AM systems that can create customizable intricate floral patterns within edible jellies [3], and have utilized AM to embed edible QR codes within food items for identification [4]. Furthermore, 3D printing has been used to increase production efficiency by reducing waste and the need for manual labor in some processes. For example, Ori-Mandu [5], uses 3D-printing to fabricate a symmetric dumpling-folding tool with customized impressions using hinges. It does so by folding a planar dumpling on itself and sealing its edges, while imprinting patterns added by the user.

With Ori-Mandu and other existing tools, the folding mechanisms are relatively straightforward, as edges of the wrappers or dough are simply pressed together to seal the food item. This limited method of folding restricts the complexity of the possible folds. For example, making soup dumplings can be notoriously challenging as it requires anywhere between 12-18 pleated folds in a twisting motion. Due to the current limitations of the available tools we propose Bake-Ori as a way to fold food wrappers and dough into more complex shapes. We do so by:

1) Proposing a hybrid fabrication method for molds using tulle cloth and origami tessellation structures for folding, creasing and patterning

2) Showcasing how Bake-Ori mold fixtures can be printed in one pass using an FDM/FFF 3D Printer
3) Demonstrating the usability of Bake-Ori molds across several cooking methods (baking, frying, steaming) and materials.

## 2. Bake-Ori

Bake Ori is a method that utilizes desktop 3D printing to create Origami-inspired tessellation molds that can fold dumpling wrappers and dough sheets into complex geometrical patterns seamlessly.

### *2.1 Pattern Choice*

Existing AM-enabled food tools, such as Ori-Mandu, feature relatively simple folding mechanisms. They use basic hinge structures that fold the dough, and the edges are pressed together to create seals. Bake-Ori, however, introduces a novel folding mechanism that is AM-enabled and inspired from origami patterns.

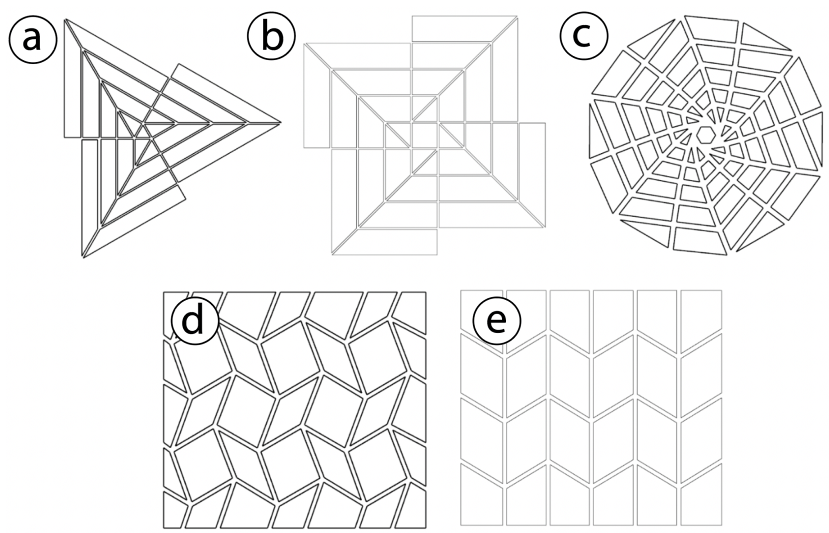


**Figure 2:** The top row contains various origami flashers: (a) regular triangular, (b) square, and (c) Starshade. (c) The Starshade pattern is the same sunflower-shape pattern that NASA used for a telescope designed to block light of nearby stars in order to better observe exoplanets. The bottom row displays Miura crease patterns.

Several folding patterns were selected for experimentation, with particular emphasis on the Starshade pattern (flasher) due to its potential for incorporating food fillings at a later stage. The Miura crease patterns were explored to demonstrate the ability to create complex food shapes and textures. This is similar to those with a preference for “wavy” potato chips over regular ones.

Additionally, another aspect of pattern that was explored was pressed impressions on the dough before cooking. Initially, the focus was on numbers and characters, but there were also experiments with simple patterns, such as a fish scale pattern. These patterns can be seen in **Figure 2**.

## *2.2 Printing Material Choice*

Polylactic acid (PLA) was selected as the printing material for the molds. PLA was chosen primarily for its food-safe properties. It is, however, important to consider additional factors to ensure the molds are fully food-safe. Due to the inherent porosity resulting from the layered nature of 3D-prints, there is a potential of food residue buildup. Without adequate cleaning, the accumulated food residue could lead to bacteria, compromising the safety of the food produced.

Although producing entirely food-safe molds was not the primary focus of Bake-Ori, simple plastic cling film was utilized to cover the molds during the production of consumable food. This temporary measure provided an additional protection to ensure the safety of the food produced for consumption.

## *2.3 Design Features and Fabrication*

Origami, traditionally performed with paper, results in structures consisting of rigid, unfolded sections and folds categorized as either mountain or valley folds. An example for the Miura pattern can be seen in **Figure 3**. To replicate this characteristic, Bake-Ori uses thin, rigid pieces to act as the unfolded areas and incorporates fabric for the mountain and valley folds.

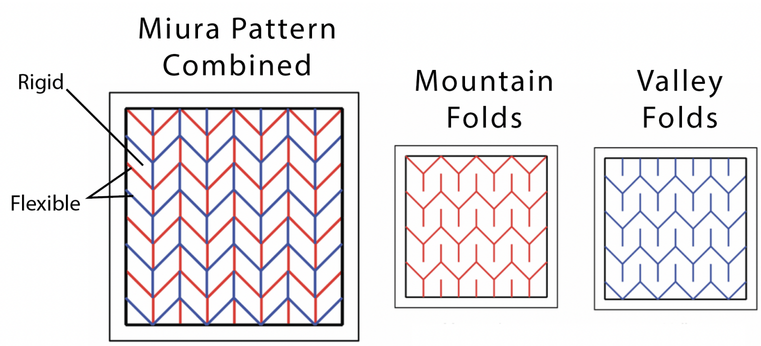


**Figure 3:** The Miura Pattern with the red and blue lines representing the mountain and valley folds, respectively. The rigid, unfolded sections are represented by the white space.

To fabricate these models, a standard desktop extrusion-based printer was utilized, with an additional step to incorporate the fabric. The molds were designed to be exactly three layers thick. The initial layer was printed conventionally. Then, the print was paused, allowing for the tulle fabric to be attached to the plate using painter's tape, such that the fabric covers the entire first layer. As the print continues, the second layer is printed directly onto the first layer and the tulle fabric, effectively bonding the PLA to the fabric. The print then continues as usual, resulting in the final molds consisting of rigid plastic pieces combined with fabric. This process along with some of the resulting prints can be seen in **Figure 4**.

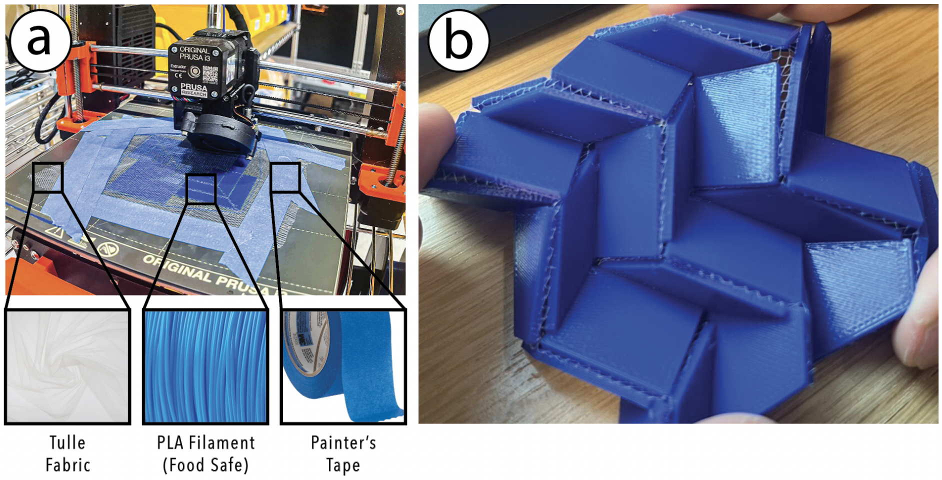


**Figure 4:** (a) The printing process using tulle fabric, PLA filament, and painter's tape to produce a mold that consists of rigid plastic pieces connected by flexible fabric. (b) A printed Miura mold.

Early prototypes featured this combination of rigid pieces and fabric, but it was quickly discovered that maneuvering proved challenging, primarily due to the difficulty of distinguishing between mountain and valley folds. **Figure 5** showcases one of these early prototypes.

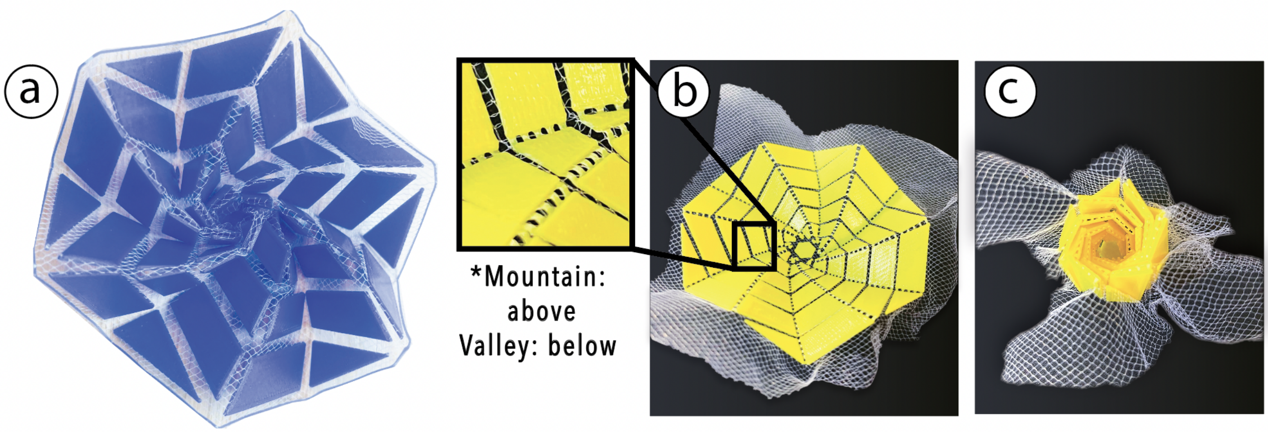


**Figure 5:** (a) An early prototype without linkages. (b, c) The prototype with the added H-bridges that allows for the mountain and valley folds to be retained. (b) In the opened configuration with the slight folds from the initial creases. (c) In the fully closed configuration.

To address this issue, Bake-Ori introduces a series of small linkages or H-bridges precisely located at each fold. Once printed, the folds only need to be creased once, and the linkages help maintain the structure of the fold. Although extensive stress testing was not conducted to determine the longevity of these linkages, one mold successfully lasted the entire duration of the expo, with approximately 50 dumplings folded using it. While some visible linkages have been broken, the final mold remains usable.

Finally, Bake-Ori explored the integration of pressed impressions with the folding mold. These attempts, however, presented challenges as the added thickness from the additional features made the folding process more difficult. Therefore, Bake-Ori separates the mold used for folding from the stamp used to create pressed impressions (**Figure 6**).

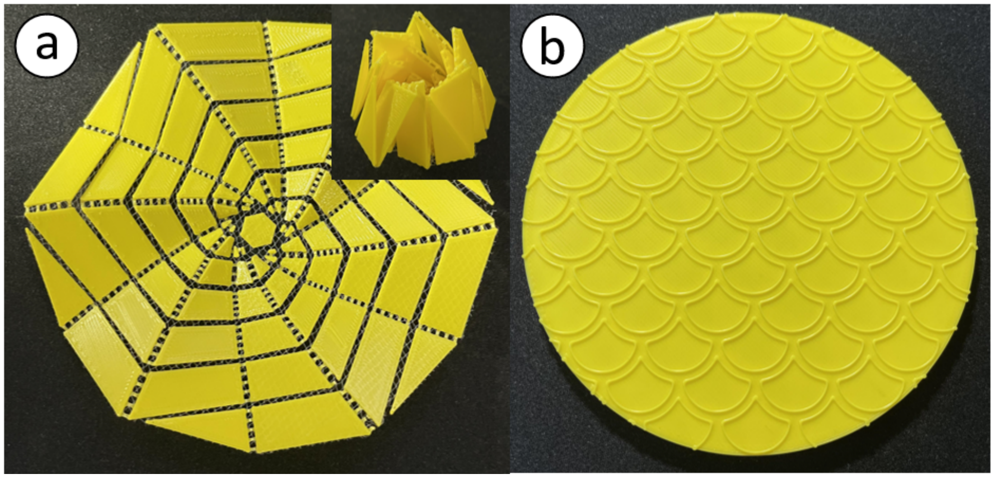


**Figure 7:** (a) Final Flasher mold with the fully folded state in the top right corner. (b) The Fish Scale stamp.

By separating the two components, Bake-Ori ensures a smoother process. The dough is first stamped to create pressed impressions. Then, the mold is used to fold the dough with the stamped impressions into the desired shape.

## 3. Implementation

In order to test and implement the 3D-printed molds, a series of experiments were performed using different food materials and cooking methods.

### *3.1 Pre-Made Dumpling Wrappers and Flasher Pattern*

To ensure repeatability and consistency, pre-made dumpling wrappers were used. The chosen mold for this particular food material was the Flasher mold. Two cooking methods were explored with dumpling wrappers: steaming and air frying.

For the steaming method, the Fish Scale stamp was first used to create stamped impressions on the wrapper. Then, the Flasher mold was employed to fold the wrapper into a rose-like shape. The process involved placing the wrapper onto the mold and following the pre-creased folds to achieve the desired shape (**Figure 7**).

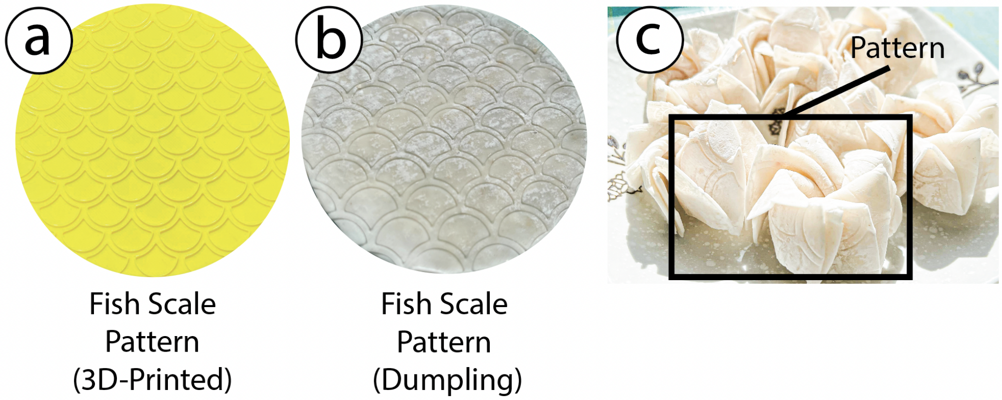


**Figure 7:** (a) The 3D-Printed Fish Scale stamp. (b) The fish scale pattern pressed into the pre-made dumpling wrapper. (c) The pre-made dumpling wrapper after folded with the Flasher mold.

While traditional dumpling fillings were not experimented with for steaming, tissue paper was used as a filling substitute to simulate the additional space required (**Figure 8**). Although the final product did not perfectly resemble the original compressed Starshade shape, it retained the same edge folds. The folded wrappers were relatively stable in shape but were frozen for a few hours to further enhance the retention of the folded structure.

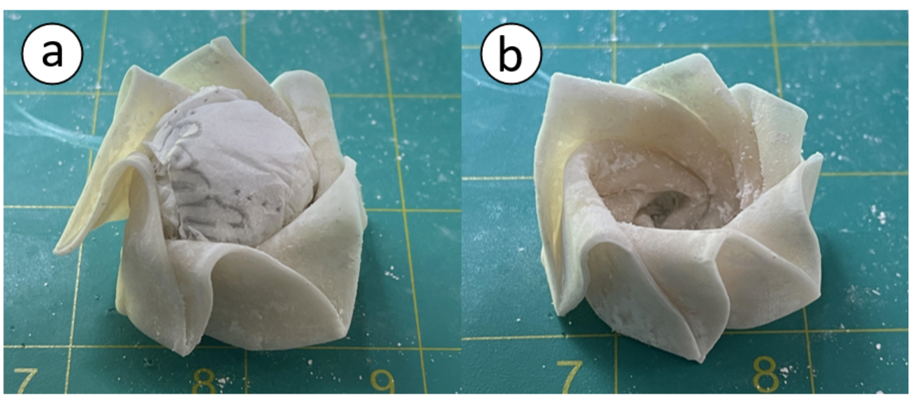


**Figure 8:** (a) Folded pre-made dumpling wrapper with tissue paper in place of regular food filling. (b) After removal of the tissue paper to show additional space for filling.

For the air frying method, a similar folding process was employed to create the general dumpling shape. As traditional dumpling fillings are malleable, it was anticipated that the filling could be added prior to folding. During demonstrations and the final expo, chocolate was used as a rigid filling for illustration purposes. To accommodate the chocolate filling, the dumplings were folded first, carefully removed from the mold, and then the chocolate was added before re-folding and enclosing the filling (**Figure 9**). To preserve the shape of the dumplings during cooking, plastic cling film was wrapped around the mold. However, the use of cling film interfered with the quality of the impressions created by the Fish Scale stamp, resulting in their exclusion from this cooking method.

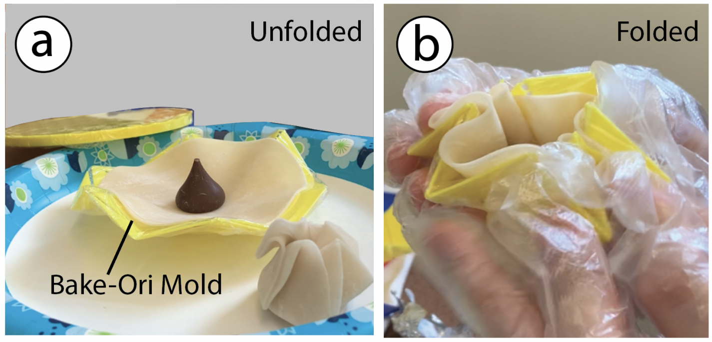


**Figure 9:** (a) The components used to make the chocolate dumplings served during the final expo. The pre-made dumpling wrapper is in its unfolded state. (b) The dumpling wrapper in its folded shape.

The prepared dumplings were sprayed with cooking oil and air-fried for approximately 13 minutes. Since the expo was a live demonstration, the dumplings were not frozen for some time as they were with the steaming method. The shape, however, was retained after cooking as well (**Figure 10**).

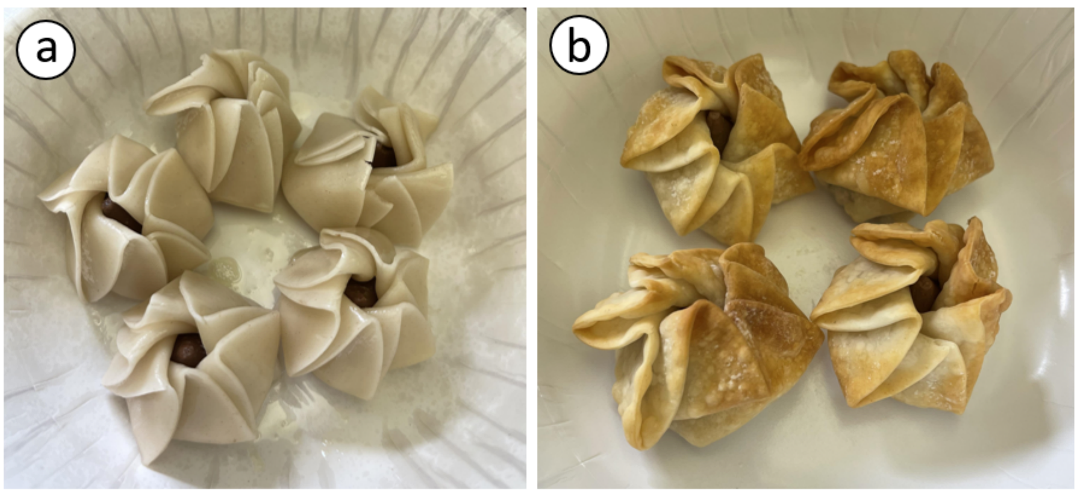


**Figure 10:** The chocolate dumplings (a) before and (b) after frying.

Overall, both steaming and air frying methods were explored with pre-made dumpling wrappers using the Flasher mold. The cooking process was tailored to each method, with specific considerations for fillings and additional steps such as freezing or adjusting the filling sequence.

### *3.2 Other Doughs and Miura Patterns*

In order to test the performance of our 3D printed mold, we tested different kinds of doughs and cooking methods in addition to the ones discussed earlier.

Below, we detail these cooking processes and their preparation methods. As showcased in **Figure 11**, we used cookie  dough then rolled it into a sheet of consistent thickness. While it is not necessary to "freeze" the sheet, we did freeze the dough for 30 minutes so that it can hold up the creases of the Miura pattern better after being released from the mold.


**Figure 11: (**a) Rolling the dough; (b) Placing the dough in the fridge to cool.

The dough sheet is laid flat, and is then folded with the Miura pattern so that it can take up its shape (**Figure 12a**). Once it takes the shape, we release the dough from the mold (**Figure 13**).

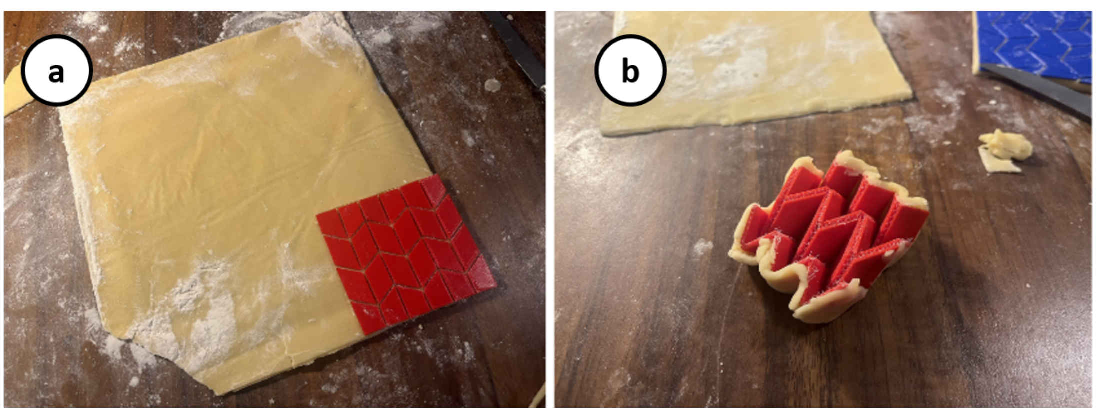


**Figure 12: (**a) Cookie dough cut to fit the size of the mold, and then (b) folded into the Miura pattern

**Figure 13:** Cookie dough taken out from the Miura mold

First, we explored baking at different dough thicknesses of dough sheets. With this exploration, we noticed that a thickness of 5mm gives a more well-defined structure to the resulting cookies/pasta. We baked our cookies at 250C for 20 minutes (**Figure 14**).

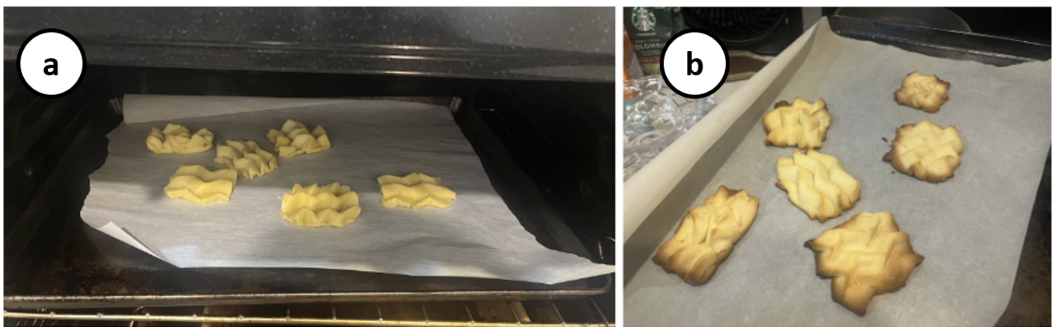


**Figure 14: (**a) The cookie dough is placed inside of the oven after release from the mold. (b) Shows the resulting baked cookies.

We also wanted to compare how baking with the mold would compare to baking without it. Generally, PLA is a food-safe material as long as it remains in its solid state. PLA's glass transition temperature is at around 60C, and its melting temperature is about 155C. Ideally, if we decide to cook with the mold, we should be below the glass transition temperature, which is the point at which the material becomes soft. However, we were able to bake our cookies at 90C in an oven for around an hour. The resulting cookies held up their structure very well (**Figure 15**)

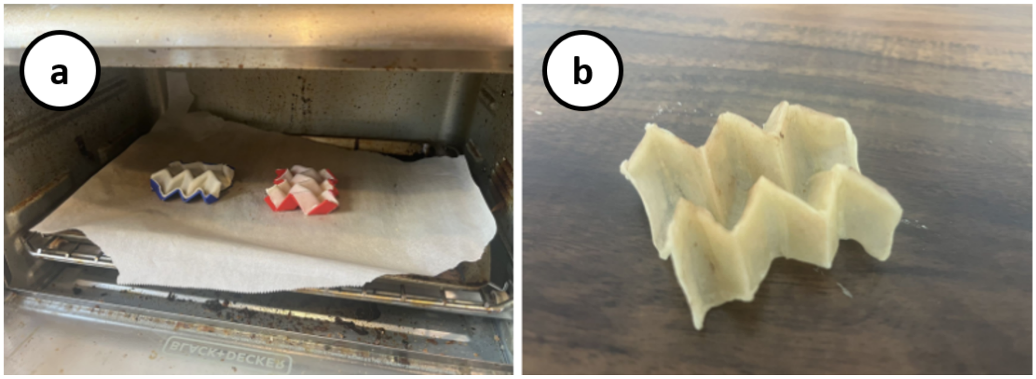


**Figure 15:** (a) Cookies baked in the oven with Bake-Ori mold. (b)The final result of the baked cookie has retained its shape.

We have also experimented with pasta dough using steaming for 30 minutes. As shown in **Figure 16**, the resulting dough pasta was able to retain its shape well.


**Figure 16:** (a) We steamed the dough without the mold. (b) Shows the final result after steaming.

To summarize, Bake-Ori molds can be used with cookie and pasta dough with different thicknesses and using both baking and steaming. However, the thickness of the dough can affect its ability to fold and retain sharp fold angles. **Figures 17 and 18** showcase different dough thicknesses.

**Figure 17:** Six samples of cooked dough using Bake-Ori 3D printed Miura mold. Different proportions of flour and water were used across both steaming and baking. The darker cookies on the left corner are a mixture of cocoa and flour.

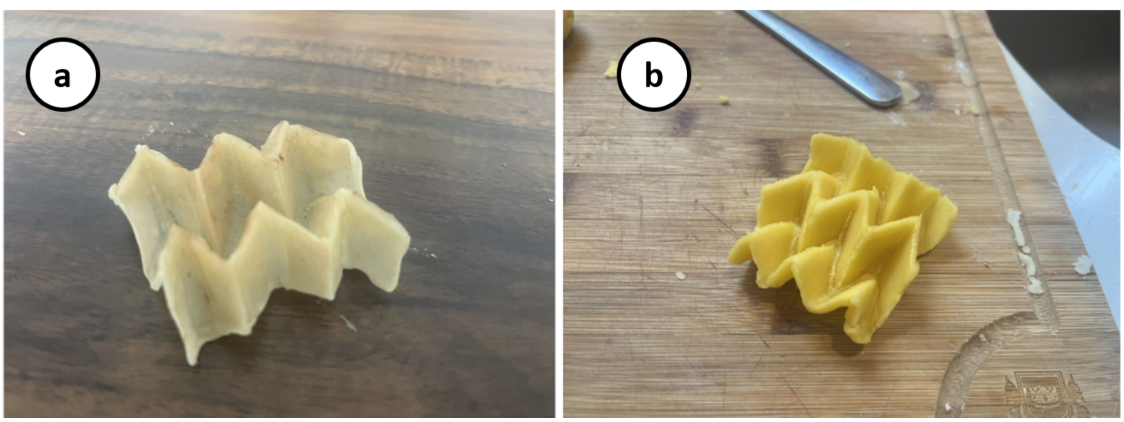


**Figure 18:** (a) and (b) showcase different thicknesses of dough that can be used with our mold.

## 4. Limitations


**Figure 19:** (a) Phyllo wrappers have also been used with Bake-Ori. (b) Shows how the thin phyllo sheet tears after the application of the flasher Bake-Ori mold on it

We have showcased how Bake-Ori can be used on pasta dough, cookie dough, and dumpling wrappers. During our material exploration testings, we have also investigated potentially using the flasher fixture on phyllo dough, which is considerably thinner in comparison to the materials used in Section 3. As seen in **Figure 19,** the phyllo wrapper tears after having the flasher mold applied to it. This is because the twisting motion from the flasher imparts just enough force to tear it, which means for thin material, molds with less twisting should be used.

An additional constraint pertains to the impact of material thickness on the precision of fold resolution in the Bake-Ori mold. To illustrate, when using thin wrappers, such as those used in dumplings, the mold folds exhibit favorable resolution with sharp angles appearing prominently. However, when dealing with thicker dough-like substances, the prominence of sharp angles diminishes.

## 5. Future Work

Due to time limitations of the semester, we were not able to conduct a user study to explore how Bake-Ori would be used by both novice and expert users. We hypothesize, based on our initial use, that Bake-Ori can introduce a more efficient process to folding complex origami patterns that are otherwise tedious to reproduce manually. For future work, we plan to provide qualitative data to support this claim. Additionally, we would like to investigate how Bake-Ori could be used as a training tool for folding dumplings and dough for children and novice users.

Finally, we explored two main tessellation structures with Bake-Ori, but would like to see how well our method can translate to more complex structures, and perhaps create a software tool that would enable users to create their own molds while inputting print impressions of their own liking.

## 6. Conclusion

In this iteration of Baki-Ori, we explored using 3D printed origami tessellations, specifically a flasher pattern and Miura pattern to fold and crease dumpling wrappers, pasta and cookie dough. We have also shown how we can add patterns, which can be user-inputted to provide more customization. These Bake-Ori molds are more advantageous than existing tools as they can fold sheets of food wrappers and dough into complex structures with consistent thickness seamlessly. We have also demonstrated how the same mold may be used across different cooking methods and food materials, while still retaining its shape, even after being released from its Bake-Ori mold.

## References


[1]  M., C. (2022) *Barilla's 3D printed pasta is now available for sale*, *3Dnatives*. Available at: https://www.3dnatives.com/en/barillas-3d-printed-pasta-for-sale-130620224/ (Accessed: 16 May 2023).

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## Section (1): Introduction & Motivation

## Section (2): Bake-Ori

Bake-Ori is a [ etc, what it is]

**Pattern Choice**:

**Material Choice**:

**Fabrication Method**:

**Design Features**:

**<u>Section (4): Implementation</u>**

(How does the folding happen?)

**<u>Section (3): Evaluation</u>**

We evaluates across different materials and cooking methods

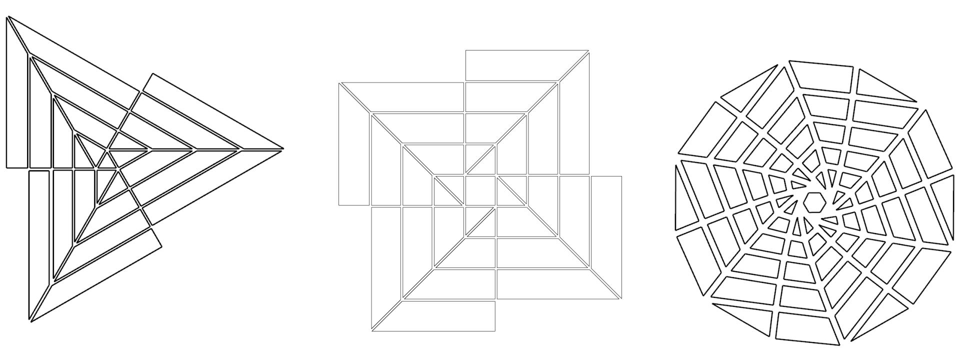
(create a table)

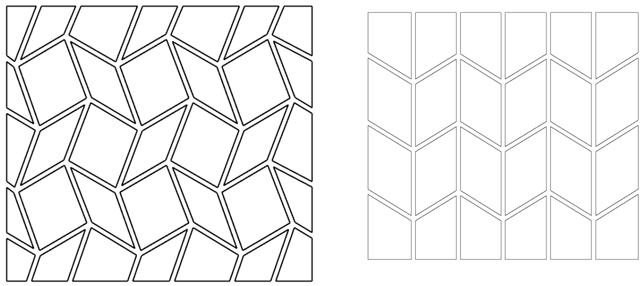
**<u>Section (4): Future Work</u>**

**<u>Section (5): Conclusion</u>**

Design and analysis

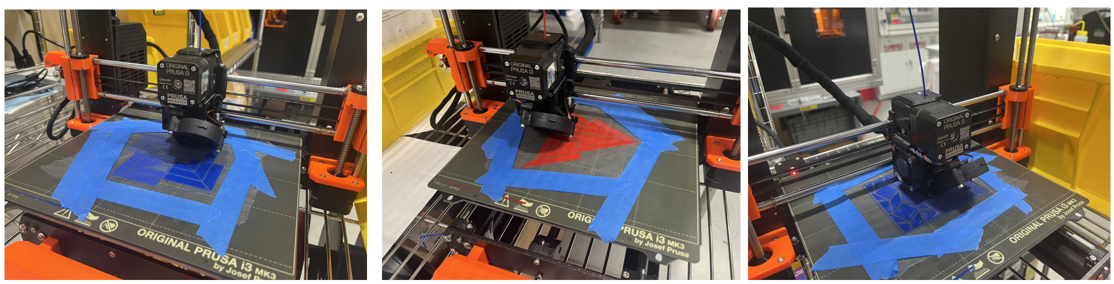
1. Origami-inspired Design
   Our origami-inspired 3D printed food molds are inspired by some of the traditional origami design, including the famous flasher patterns and the tessellation patterns.



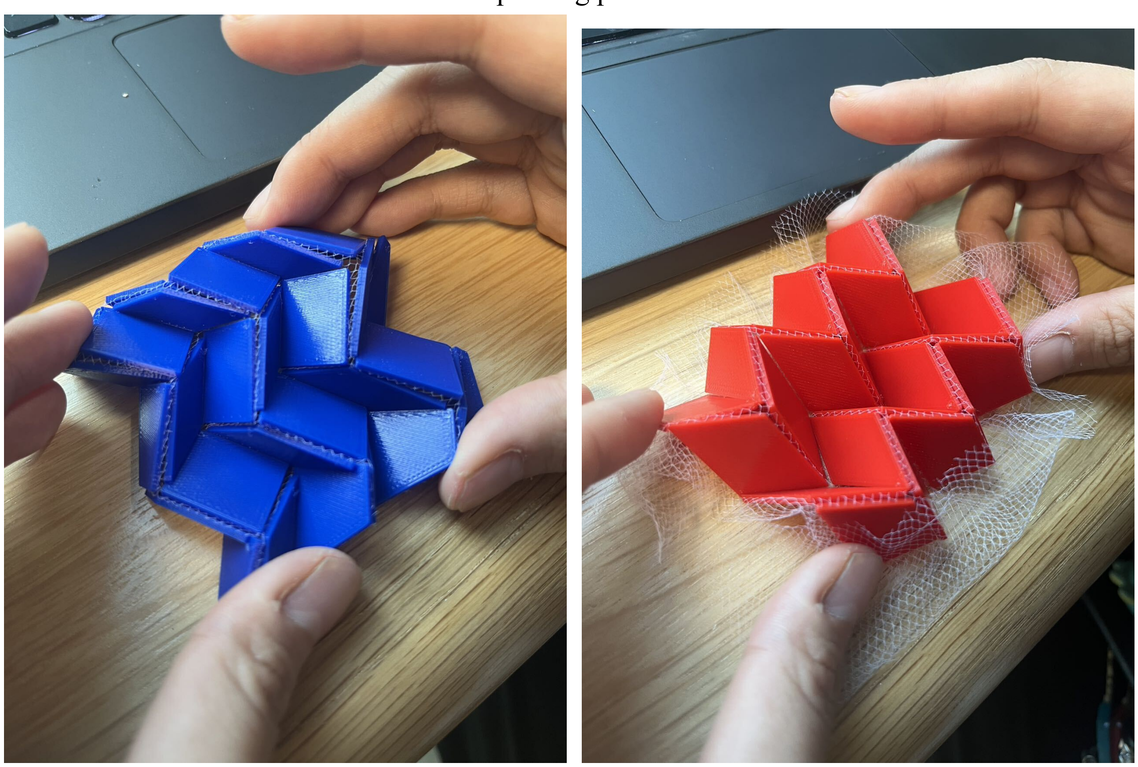


Several folding patterns are selected to be experimented in our research. (The upper line: The Flasher Pattern; the bottom line:The Miura Crease Pattern).

2. 3D printed fabrication
   In order to create the folding for the patterns, we insert a fabric inside of the 3D printing process and create gaps between patterns.

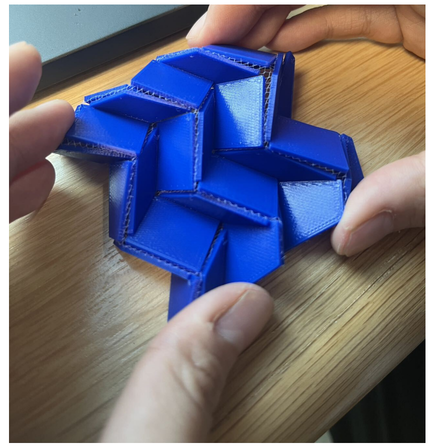


3D printing process



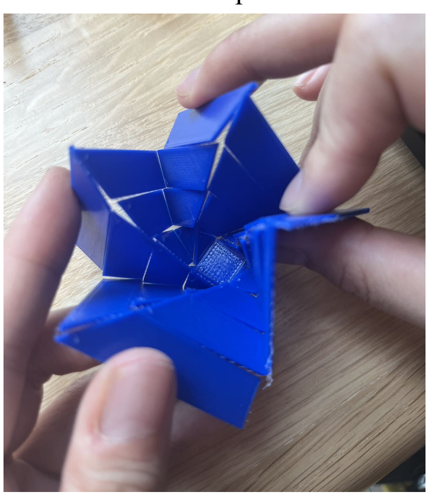
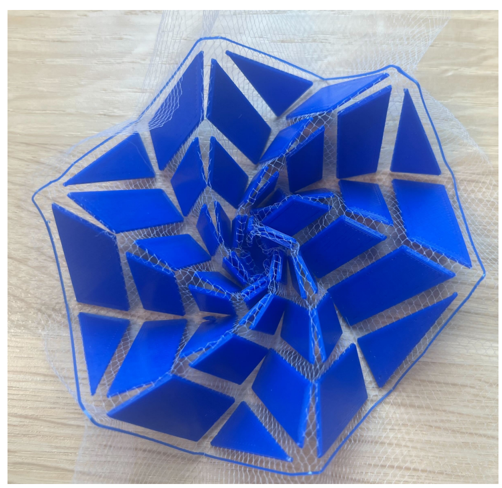
Some origami patterns that we can made by 3D printing

3. Fabrication Result
   Even though we don't get into the cooking process, we can get a sense of which kinds of origami patterns have the potential to be used in food cooking, while others can't be easily applied.
   a) The size of the patterns: If the size of the pattern is too small, it is very difficult to fold even without the dough. People have to practice a lot and remember the folding principle(fold upward or backward).

Same patterns with different sizes (the left one can't be folded easily while the right one can be achieved more easily).

   b) Even in the  same origami catalog, the left one can't be achieved while the right one with more wings can be archived easily. One of the reasons might be the right one has a more stable structure compared with the left one.

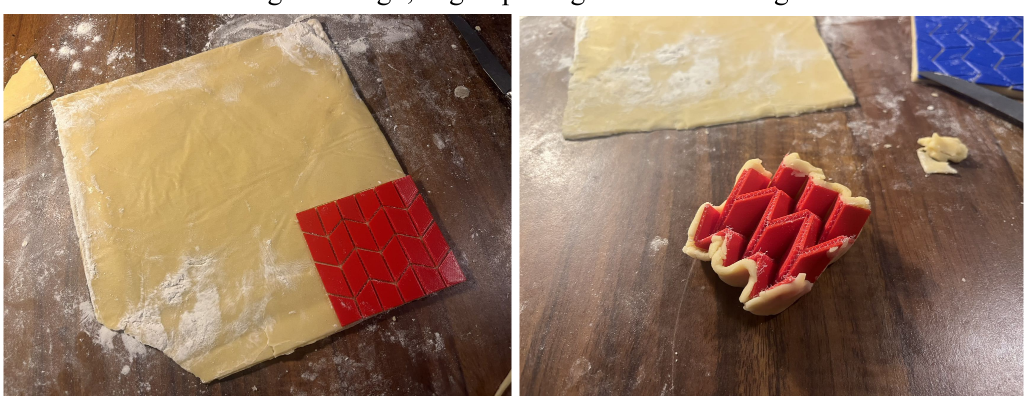



Cooking Experiments:
In order to test the performance of our 3D printed mold, we tested different kinds of doughs and cooking methods.

1. Food making process:

Left: Measuring the right proportions of flour and water; Right: Mixing the material.

Left: Rolling the dough; Right: putting them in the fridge to cool.



Left: cut the outline from the dough; Right: Folding with the mold

Taking the dough out of the mold

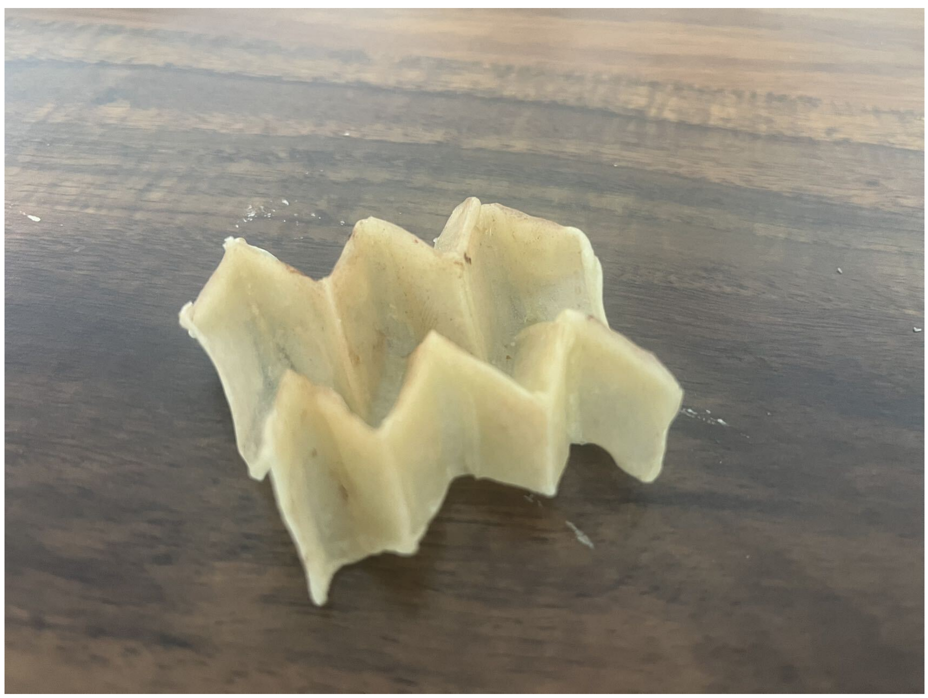
2. Frying without the mold

We put the dough inside of the bread maker without the mold and baked them for 20 minutes.

The final results of baking the dough without the molds.

3. Frying with the mold
   We know that PLA filament is a food-safe material. However, when it is in the liquid and the gas situation, it will become poisonous.  But cooking with the mold can definitely help to hold the structure. So we experiment the dough and the mold together in a bread maker in a low temperature(90C) for an hour.

We put both the molds and the dough inside the bread maker.



The final result shows that we can achieve thinner dough by putting the mold together in the bread maker.

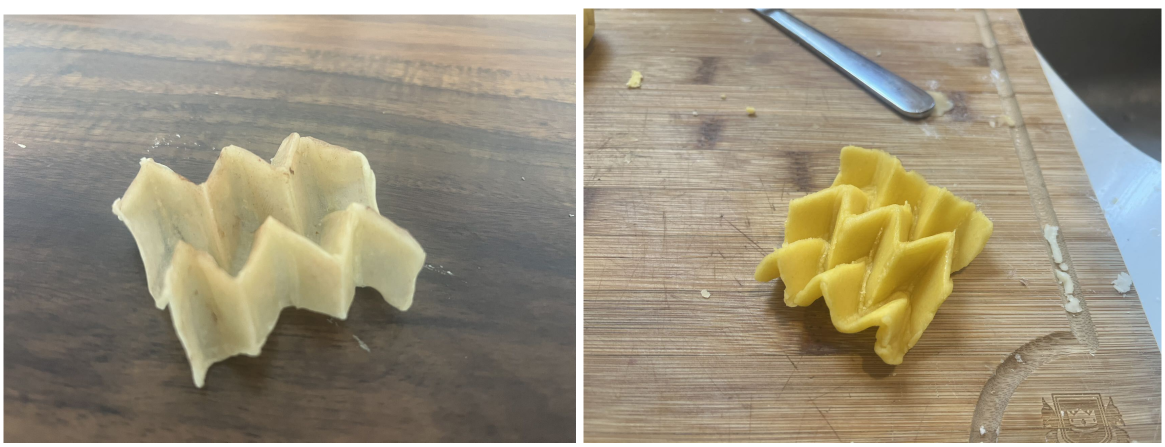
4. Steaming

We steamed the dough without the mold.

Final results after steaming.

5. Results:

Some samples are cooked with our 3D printed Miura crease mold using different proportions of flour and water, in steaming and frying methods.Then left corner one is a mixture of cocoa and flour.



Different thickness of dough can be achieved with our mold.

Conclusions:

1. When making food molds, there are several principles that we should follow when we design:
    a) The mold should not stick to the dough too much otherwise it is very difficult to separate the mold from the dough;
    b) The mold should also hold the dough when we fold them. If the dough has too many oils, the dough will slip away and it is very difficult to fold for an ideal pattern.
    c) The origami mold should have a stable structure in order to hold the dough.

2. Folding through these origami molds allows the dough to form complex shapes with sharp angles and geometric patterns difficult to recreate by hand
3. The origami mold has an advantage over similar 3D shaped molds as we start with a flat dough that maintains a consistent thickness. If we make it with a set 3D shaped mold, the sharp turns are thicker than flat surfaces as we shape it by pressuring the dough into the angles and creating uneven cooking as we are also pressuring the surrounding dough with our finger instead of just the tip of the angle.
4. With our methodologies, we can create special patterns for the food, especially creating a perfect product that can be used in  the fine-dining restaurant.  Here are two examples: we put our dough as the dishes with decorations.