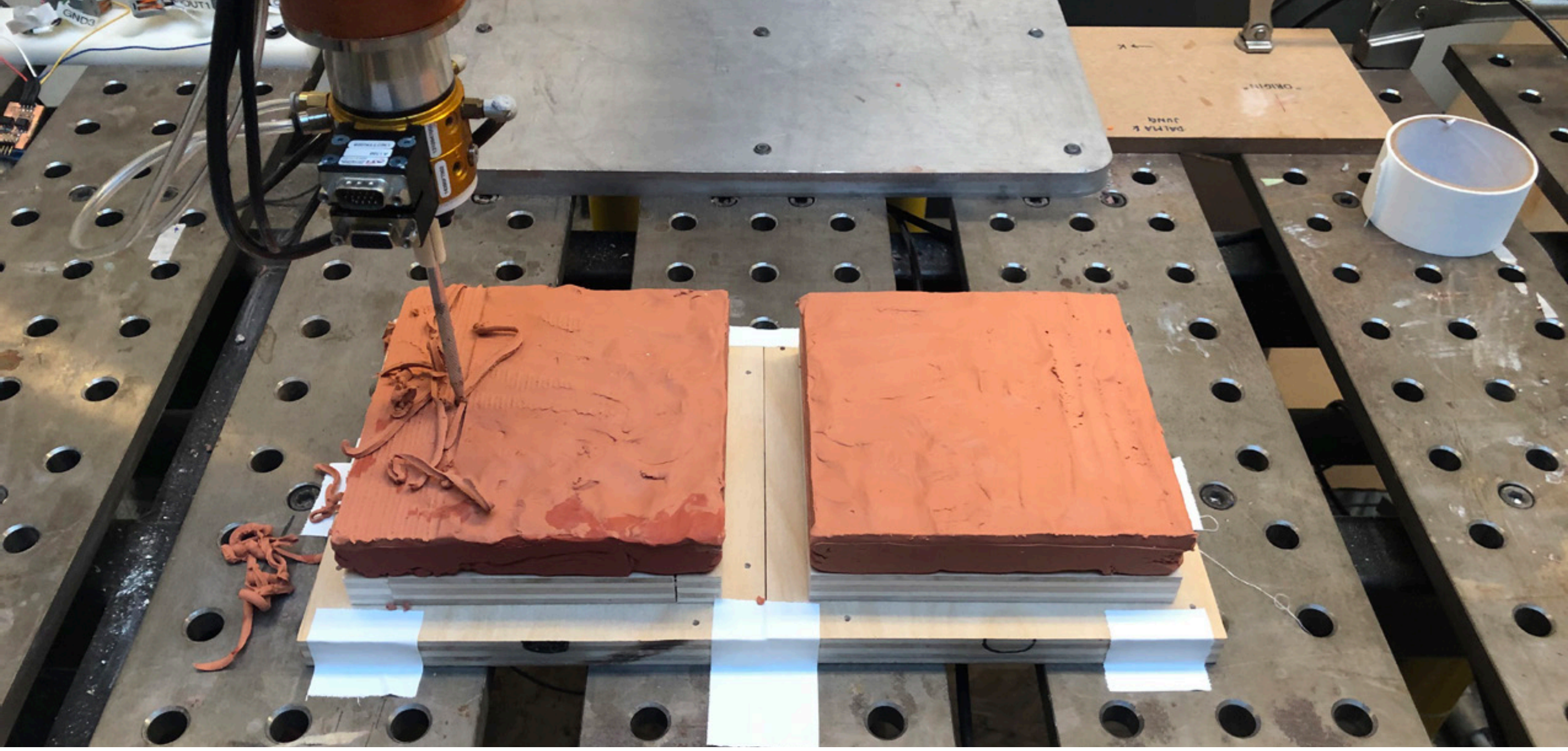

Fig. 1 Flattening hand-formed clay blanks for in preparation for carving

Many Molds:
Robotically Carved Materially Reconfigurable Molds

Gil Sunshine

Abstract Questions surrounding materiality in architecture, and related issues of embodied carbon and waste, often focus on the finished product or building. We ask, how many tons of concrete or steel went into the structure? What is the provenance of the timber cladding on the facade? There are, however, auxiliary materials on the building site and factory floor that are largely out of view, but deserving of consideration. The materials used to make the molds used to cast building components fall into this category. This paper presents preliminary research into the use of reconfigurable, and therefore reusable, materials in mold making.

1. **Introduction**

Mold making and casting are interdependent technologies that encompass a wide range of techniques and material processes. Broadly speaking, however, molds have traditionally been used for two reasons: first, they are capable of producing many identical castings; second, they allow for the transformation of a pattern of one material into a casting of another material with different properties. For example, a form might be carved from an easily worked material, such as wood, and cast from a less workable but more durable material like steel.

Humans have been making molds to reproduce or mass produce objects since as early as the Neanderthal age (Boon 2010). In recent years, as the appetite for mass customization has grown, there has been increasing interest in adapting the logics of nonstandard seriality to the material processes of mold making and casting. To borrow Mario Carpo's analogy, whereas the traditional mold might be understood as the 3D version of the woodblock used to produce many identical prints, the mass customizable mold is more akin to the movable type printing press where letters can be rearranged to produce infinitely variable information and meaning (Carpo 2011). In a somewhat ironic twist, the very technology that the modern world of repetition and standardization was built on is now reimagined as a site of exploration in the production of difference.

This project explores the use of malleable materials, specifically non-hardening clay, in the mold making process to allow for reconfigurability and reuse of molding material. Clay is formed into blanks and robotically carved, producing molds without the need for a pattern, also referred to as a model. The matter used to produce a single mold can be used to make multiples of a given object and endlessly reconfigured to produce many unique casts.

2. **Related Work**

2.1 *Mechanically Reconfigurable Molds*

Patents for mechanically reconfigurable molds emerged in the United States starting in the late 1800's (Galizia, et al. 2019). These molds fall into two categories. The first can be understood to be much like a pin screen where a matrix of discrete elements can be repositioned prior to forming (fig. 1 and 2). The second category of reconfigurable molds that emerged during this time are modular molds where sections of a mold can be changed out to produce different casts. Today, these modular molds are widely used in industry, whereas the molds made of a matrix of discrete adjustable elements are less common (Galizia, et al. 2019). However, related research into deformable membrane molds has continued alongside the prevalence of the double-curved surface in architecture (Pronk 2009).

2.2 *Materially Reconfigurable Molds*

Materially reconfigurable molds, most notably sand molds have been in existence since as early as the bronze age (Nørgaard 2018). Today, sand molds are ubiquitous in the foundry industry. In foundry applications, sand is mixed with water and clay to make green sand which is typically packed around a pattern that is removed before filling the mold with molten metal. After a cast is made, green sand can be reused after readjusting for moisture and chemical properties. However, the recycling process can only be a repeated a limited number of times before the waste foundry sand goes to landfill. (Sabour, et al. 2020). In sand molds, the material used to make the mold is reconfigurable, but typically the pattern is intended to be fixed in its formulation.

Part of the Tailorcrete initiative, Gramazio Kohler's "Zero Waste Free-Form Formwork" uses a robotically actuated surface (a mechanically reconfigurable mold) to cast wax forms which are then brought to site and used as concrete formwork. These wax pieces can then be melted down and reused and therefore can be understood as materially reconfigurable molds.

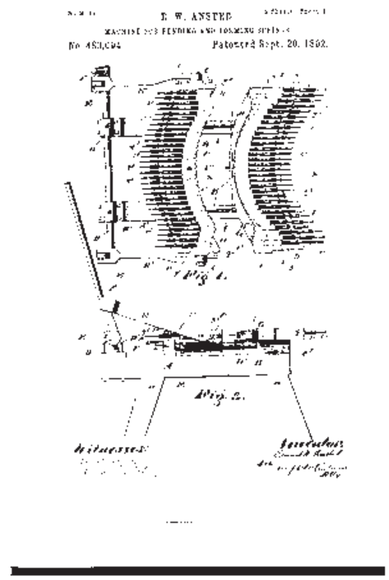

Fig. 1 Machine for Bending and Forming Springs. An early example of a Mechanically Reconfigurable Mold

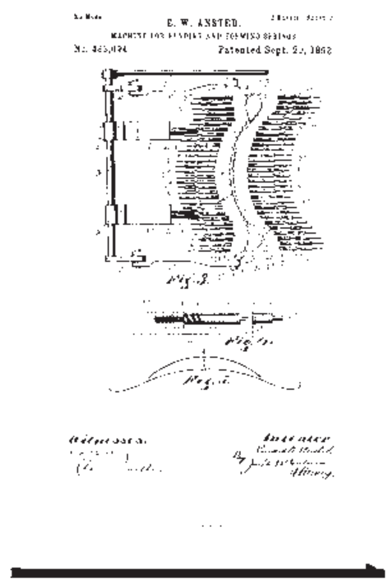

Fig. 2 Machine for Bending and Forming Springs. An early example of a Mechanically Reconfigurable Mold

2.3 *Robotically Carved Molds*

This project also draws on earlier research related to direct carving a of molding material with a robotic arm (Clifford 2014 and Schwartz 2013). The benefit of directly carving the negative of a form for molding is that becomes unnecessary to produce a pattern, saving time and material.

2.4 *Material Indeterminacy*

The use of the relatively plastic non-hardening clay presents both challenges and possibilities associated with material indeterminacy. This is to say, the molding material does not always perform in a predictable manner. Previous research has looked at how material indeterminacy can come up against digital simulations and fabrication processes in productive ways (Johns 2014 and Oesterle et al. 2007).

3. **Methodology**

The prototypes described in this paper are the result of line and point based toolpaths. The geometries that were chosen do not relate to any specific function or meaning, but instead were developed in order to explore a range of options in the design space. Plywood flasks are filled with non-hardening clay to produce blanks. These blanks are then flattened to ensure proper alignment with the robot arm. Once flattened, the blanks are carved or formed by simple tools attached to a robotic arm and finally cast from hydraulic cement (Rockite). Casts are then excavated from the molds and the clay is cleared of any pieces of cement before being repacked into the flask for reuse.

3.1 *Tooling and tool paths*

Like many robotic fabrication projects, this project began as a translation of an extant fabrication process (the carving of clay by hand) into a digitally controlled one. As such, the tools used in the first place were off-the-shelf metal carving tools for clay. An end effector was printed in PLA that holds the tools by friction fit. This allows for the easy exchange of one clay carving tool for another. For the prototypes described in this paper, two off-the-shelf carving tools were used for the removal of clay. The first is a 3/8" wide flat tool that was used to flatten the clay blanks before carving the mold. The second is a tool with a 1/4" diameter wire circle at its tip. A custom end effector was also printed with a 1/2" diameter sphere at its end in order to create registration holes. This end effector was later used to form molds by displacing material rather than carving. To summarize, two sets of clay tools were developed: one set for "stroking" and one for "poking".

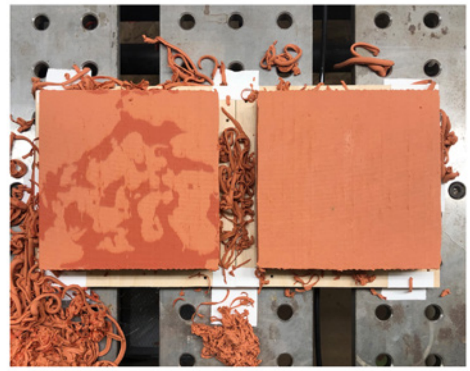

Fig. 3 Clay blanks that have been flattened

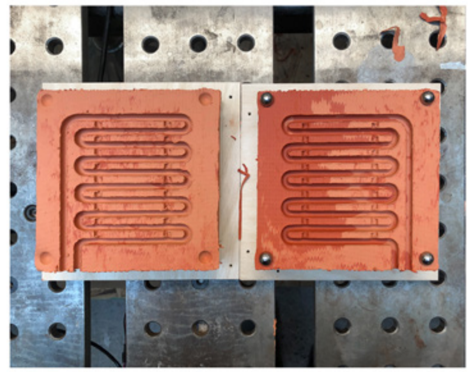

Fig. 4 Carved mold with ball bearing keys

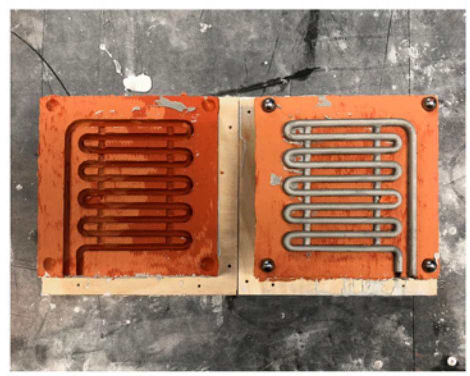

Fig. 5 Cast form waiting to be excavated

Fig. 6 Excavated cast form

Two types of tool path were generated for these two types of end effectors. For the end effector fitted with a clay carving tool, 3D curves were drawn in Rhino with tool paths generated in MasterCAM and Robotmaster directly from those curves. Generating tool paths from curves to carve a cavity in the mold produces the appearance of an extrusion process in the cast positives. For the end effector fitted with the 1/2" diameter sphere, peck drilling toolpaths were generated from points placed in Rhino.

Two or more sprues are always built into the toolpath to help ensure the flow of cement through the mold and to allow air to escape.

3.2 *Materials and Material Indeterminacy*

For these studies, off-the-shelf non-hardening clay was selected as the molding material. Going forward, an exploration of a range of molding materials would be beneficial, but non-hardening clay was selected as it strikes a balance between being easy to carve and holding its shape after carving. In cases where the molding material must be rigid, e.g. in the use of plaster molds in slip casting porcelain, overhangs and draft angle are an important consideration. A benefit of using a malleable material like clay as the molding material is that this is not a concern.

The relative plasticity of the non-hardening clay results in a situation where the clay can be deformed or pulled along with the carving tool in unexpected ways. As a result, the order of operations in path planning becomes key. This might be viewed as a problem if absolute control over the system is desired. In this case, however, these deformations serve as a welcome expression of the material process at play, where the molding material is of equal if not greater importance as the casting medium in terms of the character of the final object.

This observation, which occurred early on in the research, inspired an exploration into deformation based forming using the "poking" end effector. The process required for the deformation based forming is slightly different. First, material has to be removed from the flattened blanks or there will be no cavity to receive the cement (figure 7). In the example shown in figures 7-10, an array of points was first used to make impressions in the mold. An offset of this array produced the next set of toolpaths, which have been executed in figure 9. The arrangement of points and order of operations was based on some level of intuition about how the clay would perform. No attempt was made to digitally simulate material deformation. The process produced something akin to an egg-and-dart pattern in the cast form.

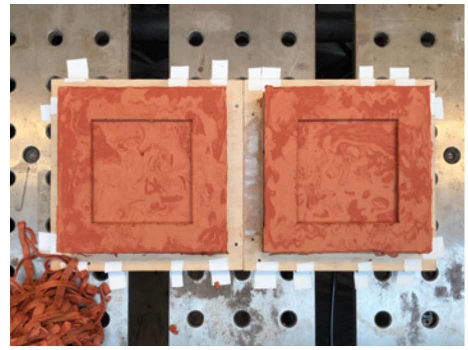

Fig. 7 Cavity carved in flattened blanks

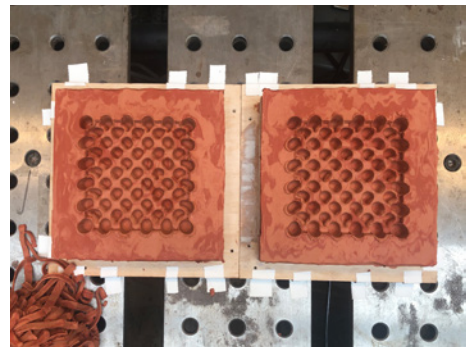

Fig. 8 Initial impressions made

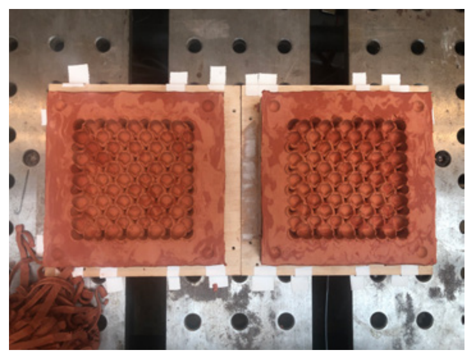

Fig. 9 Offset impressions made

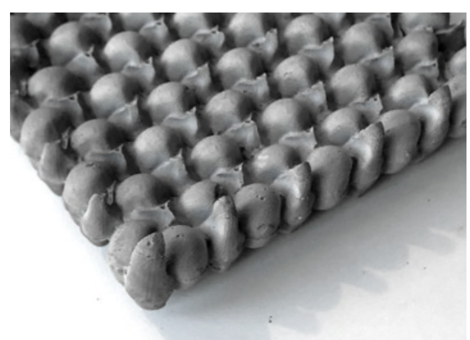

Fig. 10 Detail of cast

3.3 *Registration*

An essential component of a two (or more) part mold are the keys which allow for one half of the mold to register to the other in exactly the right position. Typically, registration keys are manifested as an indent in one half of the mold and a protrusion in the other. In the case of the clay mold, this would be possible, however, it would require significantly more carving time when surfacing the mold. Instead, aligned indents were made in either half of the mold using the 1/2" ball end effector. When closing the mold for casting, 1/2" ball bearings were inserted into these impressions to key together the two halves. This solution was effective in most cases, however, due to the elasticity of the molding material, there was some variability of results.

3.4 *Offcuts*

Throughout the carving process, strands of clay are constantly being produced. These have the potential to clog the carving tool or generally get in the way. As a result, a great deal of time is spent chasing these strands. Moving forward, an automated system for cleaning the carving tool would be beneficial.

Fig. 11 A family of casts made with curve based toolpaths

6. **Conclusion**

This paper presents preliminary research into the use of malleable materials to produce materially reconfigurable molds. The process offers several benefits relative to traditional mold making and casting. First, whereas traditional mold making is useful for reproducing an existing pattern in a new material or mass producing many copies of the same form, this process allows for the mass customization of form within the limitations of the system. Mass customizable formwork is of course not a new idea, but often uses subtractively fabricated single use molds, producing a tremendous amount of waste material. This brings us to the second benefit of this system: material reuse. With minimal processing, the non-hardening clay can be easily reused. While the process to produce the molds is subtractive, unlike milling plywood for example, it does not transform the material that is removed and therefore is non-destructive.

In addition to pursuing further iterations and increased complexity under the current process, several research trajectories revealed themselves over the course of this research. Two are of particular interest. The first would involve scaling up the process of the robotically carved molds to produce architectural scale elements. Rather than using non-hardening clay, an exploration of earth as molding material might be explored in this case. Second, questions of materially indeterminate molding materials seem promising. These explorations reveal the mold making process in the final outcome of fabrication, and therefore have the potential to make visible the auxilliary materials of making.

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