UTILISATION OF ADDITIVE AND SUBTRACTIVE DIGITAL FABRICATION PROCESSES IN THE MANUFACTURE OF MOULDS FOR CERAMIC SLIP-CASTING

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ABSTRACT

This paper intends to illustrate and discuss three alternative approaches in the forming of plaster moulds for ceramic slip casting. The first process being the utilisation of 3D printing for the creating of mould-making patterns from CAD generated files, and the second being the direct CNC cutting of the ceramic slip-casting cavities straight out of pre-cast Plaster of Paris blocks. The third approach involves CNC cutting a slip-casting mould and dip-casting into ceramic slip. The generation of CAD files was done with SolidWorks, 3D printing undertaken with a low-end FDM 3D printer, and toolpath generation for CAM processing done with Rhino & RhinoCam, and CNC Cutting undertaken on a small-bed HIGH-Z milling machine.

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1. INTRODUCTION TO CERAMIC SLIP CASTING

Slip casting is a ceramic manufacture process used to create hollow vessels or products with an even wall thickness. Slip casting is a filtration process, in which a thin slurry or 'liquid casting slip' (a mixture of dry clay, water and deflocculants[2]) is poured into a mould made from a hydroscopic plaster most commonly Plaster of Paris. The porosity of the Plaster of Paris (recommended mixture 1.3kg of Plaster to 1l water, for optimum strength and porosity) causes a capillary action and the mould withdraws the liquid (filtrate) from the slip. As the liquid is 'sucked' into the mould, the suspended clay particles are forced towards the mould walls leaving behind a stiff layer of clay particles on the wall of the mould, creating the even wall thickness of the final product/vessel. After a length of time, usually between 7 and 10 minutes, determined by the desired wall thickness on the part/vessel, the remaining liquid slip is poured out of the mould back into the slip bucket or container. As the clay dries, it shrinks and pulls away from the sides of the mould and can be released for further drying, fettling and firing [1].

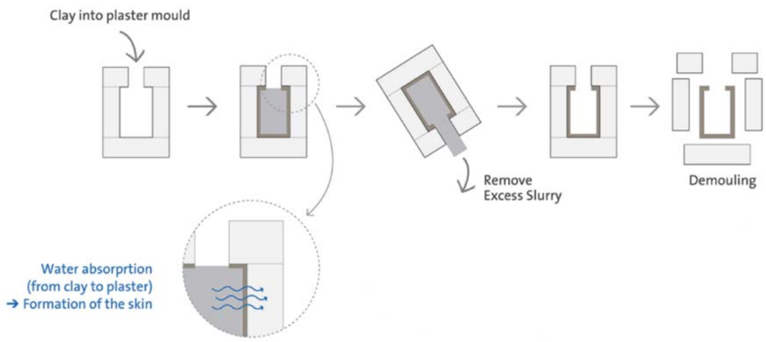


Figure 1: Slip Casting Process. Online.

2. THE DIGITAL-HANDMADE

Ceramic production technology has not advanced significantly over the past centuries. However, the recent advancements and accessibility of digital fabrication software and machinery has lead to the growth of a digital revolution in ceramics of "digital crafting" whereby designers explore new relationships between the hand, traditional skill and digital technology, combining cutting edge fabrication with craft traditions through the use of digital design, tooling and manufacture [2].

3. PATTERN AND MOULD MAKING : PROBLEM AND OPPORTUNITY

The first step in mould making process for slip casting is the modelling of a master model of the desired form known as the original, pattern or positive. Modelling involves the art of manipulating a malleable material, such as clay, plasticine, modelling clays, wax, papier-mâché, synthetic foams and wood [4].The process of modelling is heavily time intensive and requires a great amount of skill and craftsmanship. Furthermore, master models made from materials such as clay, wax and foam, can only be used to create one mould as they are distorted or destroyed when removed from the plaster mould. Therefore multiple identical master models need to be made if more than one mould is required. From a design point of view, this is a limiting factor as the form giving, level of detail or complexity and replication that can be achieved is limited to the skill of the maker.

The process of building the mould itself can also be a time and labour intensive process when a multiple part mould is required. First, the maker identifies and accurately marks out the split lines/ seam lines on the part, ensuring that there are no undercuts. The number of mould parts is determined by the form of the final product and the defined split lines. Second, a frame or box in which to cast the plaster must be built or assembled. Clay walls are then built around the part (along the split lines) sectioning areas in which to pour each mould part. Once the first part has been cast it must be left to dry sufficiently (drying time is dependent on mould size, wall thickness, ambient temperature and moisture). Alignment keys are then hand carved into the part prior to casting the next section. These steps are repeated for the casting of each section of the mould.

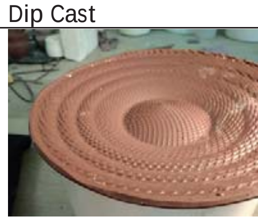
[2] Deflocculants evenly suspend and align particles the clay-water suspension, increasing fluidity [3]

1 Finished wooden prototypes of various vessels sealed with polyurethane. 2 Turn a solid, laminated MDF form on a lathe to get close to the right profile. 3 Finish shaping the prototype on a band saw and draw seam lines. 4 Add a clay slab to the sealed prototype to create a pouring gate or slip reservoir.

Figure 2: Mould Making Process, Online.

Incorporating CAD & CAM software and machinery into the process of mould making offers great opportunity for increased design complexity and detail as well as increased production efficiency. The following consists of three approaches to transforming the mould making process though the incorporation of 3D printing in the pattern-making process, and CNC Cutting in the mould-making process.

Table 1: Various methods tested and discussed within this paper.

	Method 1	Method 2.1	Method 2.2	Method 3
	3D Printed Master Model + Slip Cast	CNC Cut Moulds + Slip Cast		CNC Cut Positive Mould + Dip Cast
				
Master Model	3D printing master Model	No model needed	No model needed	No model needed
Plaster Mould	3 Part Poured plaster mould	1 Part CNC cut plaster mould (Rough cut + Spiral cut)	3 Part CNC cut plaster mould (Rough cut + Parallel finishing)	1 Part (Positive) CNC cut plaster mould (Rough cut + 2 different spiral cuts)
Casting Method	Slip Casting	Slip Casting	Slip Casting	Dip Casting (Variant of Slip Casting)

4. METHOD 1: 3D PRINTING MASTER MODEL AND SLIP CASTING

The incorporation of 3D printing in this sequence allows for a master model to be created directly from a CAD model using 3D printing. The sequence illustrated below illustrates an example of this in the creation of a small faceted planter to be cast from black ceramic casting slip. The initial CAD form was created in SolidWorks which was a solid geometric faceted form modelled with solid modelling feature steps. This SolidWorks file was imported into the UP! Mini 3D Printing software and printed using ABS plastic filament. The printing of the 3D Pattern was done with a hollow honeycomb fill to decrease material use and lower the problems of warpage. The 3D printed master model was smoothed and finished with various spray filler, primer and sand paper grades prior to it being used to create a 3 part poured plaster mould. The creation of the 3 part mould was done with conventional ceramic practices where a structure is built around the pattern to create the 3 mould parts in three stages. Following the traditional slip casting process, the faceted planter form was slip-cast. Figure 3 shows the 3D printed master model, the 3 part mould; and final fired geometric planter.

Figure 3: 3D printed pattern,3 part slip-cast mould and hollow ceramic planter. Final planter cast in black slip and fired (right image).

The part was fired to low stoneware, 1200°C, higher than the recommended firing temperature of 1160°C, resulting in bubbles and imperfections in the part surface. A second firing at 1180°C yielded a much more satisfactory outcome with less warping and surface imperfections. Once fired to full temperature, shrinkage is generally around 7%, however this final ceramic form was measured and compared to the 3D print allowing for the final shrinkage rate to be identified as being 8.5%. Now that the shrinkage is known to be 8.5%, any future products made from CAD models can be scaled up in the CAD environment prior to 3D printing, allowing the final fired outcome to be as near as possible to the intended final size.

5. METHOD 2.1: CNC CUT, ONE PART MOULD (NO PATTERN NEEDED)

The second method attempts to eliminate the pattern making and mould building step/process altogether by subtractive milling the mould cavity from a pre-cast block of Plaster of Paris. In the example below, a SolidWorks Part file of a small soap dish was imported into Rhino, and a Boolean subtract command subtracting the dish from a solid rectangular block creating the mould form. This was then prepared for cutting using RhinoCam. The cutting sequence used was 4 layers of horizontal roughing, followed by a spiral cut starting at the lowest centre spot of the mould. The cutting bit utilised was a 6mm Tungsten Carbide end-mill. The CNC cutting was undertaken using a prepared cast block of Plaster of Paris mounted within a small desktop router (High-Z CNC Router). The mould was then used to slip-cast black ceramic dishes with a final wall thickness of approximately 2mm. These were then fired once dried. This sequence is visible in Figure 4.

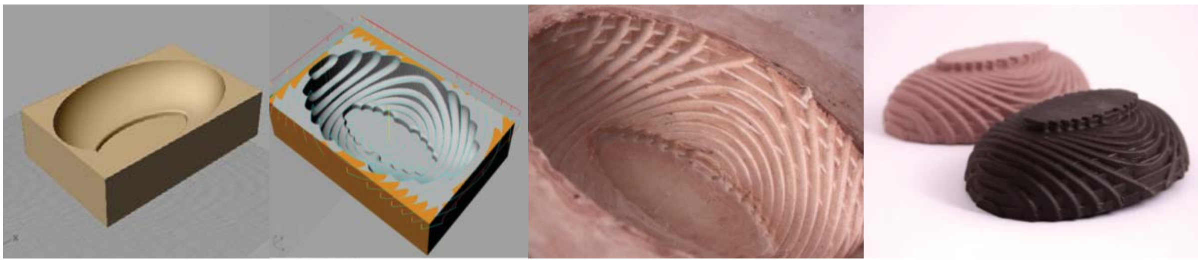


Figure 4: CAD file to final slip-cast and fired ceramic bowl. The Spiral CAM path and rough-cut levels are evident in the final product aesthetic.

6. METHOD 2.2: CNC CUT, 3 PART MOULD (NO PATTERN NEEDED)

To further test the complexity achievable with this method of mould making, the development of a 3 part mould was undertaken using SolidWorks. This allowed for the calculation of the shape of the form to allow effective staking. The intended function of this vessel was to be a small stacking pot for spices or tea-bags. Once the CAD file seemed suitable, the NC code was prepared to cut the file directly out of several blocks of pre-cast plaster. Cutting was done when the plaster was not completely dry, but slightly damp. It was suggested that the plaster, if slightly damp, would prevent chipping in the plaster (ensuring a neater cut) and reduce the generation of and inhalation of fine dust (Figure 6).

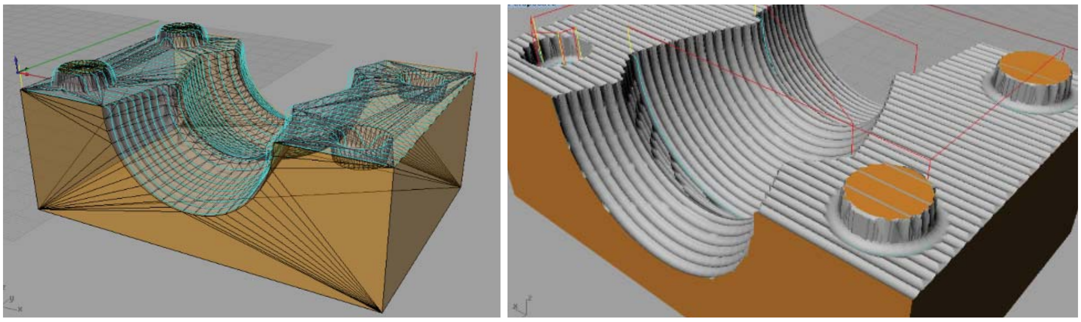


Figure 5: CAM cutting paths set to Rough cutting, and Parallel finishing (illustrated) Rhino and RhinoCam used for creating paths.

The cutting bit used was a standard 6mm High Speed Steel drill bit (HSS) because no other router bit was available to reach to required cutting depth. It ended up cutting the plaster relatively effectively as the double flute allowed for effective chip removal. Although it may not perform as effectively as a dedicated CNC cutting bit, it has the benefit of being very low cost and easily replaceable for around R20 from any hardware store (figure 6).

Figure 6: CNC cutting mould parts from Plaster of Paris blocks.

A problem with the CAM cutting sequences was that it was problematic to select specific faces to be highly finished, and some faces to be left with rough surface marks. This may be restrictions in the NC software (several years old), or in the limited understanding of the CAM software (figure 6, far right). The mating faces of the moulds were therefore smoothed with a craft knife until the parts fitted together effectively (to avoid running of slip between mould parts, and the need for extra fettling after casting). Black casting slip was poured through a sieve (to remove any clumps of clay particles which would cause impurities or bubbles in the part's wall) and into the mould cavity. After 8 minutes, excess slip was drained from the mould (figure 7 sequence).

Figure 7: Slipcasting with black ceramic in the 3 part CNC mould.

Once the cast was leather hard (hard enough to handle without distorting the form), it was removed from the mould and allowed to dry overnight. Thereafter, the rim and split line were fettled by hand using a fettling knife. These casts were fired at 1170°C (60°C per hour to 200°C, to remove all moisture from the part, and then 100°C per hour to 1170°C). A lower temperature was used in order to avoid warpage, especially in this case of achieving a stackable vessel. The final stacking pots are illustrated in figure 9. The pot with the white surface pattern was done by drizzling white casting slip into the inside of the mould cavity prior to filling with black slip.

Figure 8: Firing the ceramic casts undertaken using ramp cycle totalling approximately 16 hours, with a maximum temperature of 1170°C.

Figure 9: Final fired stacking pot showing colour, stacking and surface detail.

The outcome effectively shows the ability for the forms to stack, as well as provide evidence that the cutting texture of the drill bit also created a unique and interesting aesthetic (figure 8). Additionally the gritty texture of the clay added to the digital hand-made outcome.

7. METHOD 3: CNC CUT MOULD (POSITIVE) AND "DIP CASTING"

While researching different approaches to ceramic casting, the following video was seen online where a positive form was dipped into a bucket of slip as opposed to slip being poured inside of a mould (figure 10). This alternative approach allowed for the layer of slip to form on the outside of the plaster form, and once dry enough, will fall off of the form. That is with the suitability of the plaster form to allow this to be removed. This seemed like an interesting approach and we decided to replicate this, however with a CNC cut master model.

Figure 10: Chudy and Grase Dipped, a ceramic dipping structure, Online.[5].

The cutting of the positive dip casting mould was done with the same CAM sequence preparation as was used in the previously described 3 part mould. The source plaster was cast in a 220mm diameter by 70mm cylinder stock. The form was created in SolidWorks with a basic Revolved Protrusion command (figure 11), the file brought across into Rhino, and the CAM sequence created with RhinoCam. The cutting sequence included rough cutting layers at 150% bit thickness to remove the majority of the material, thereafter 2 different spiral cut steps with a 66 % and 80% step-over respectively. This large step-over would allow for pronounced cutting lines adding to the aesthetic of the form. The centres of the spirals were deliberately placed away from the centre of the form as the asymmetrical pattern was desired. The form of this part could not be too deep as the shrinkage of the casting slip while drying would pull onto the form as opposed to pulling away from the mould as in the standard slip casting process.

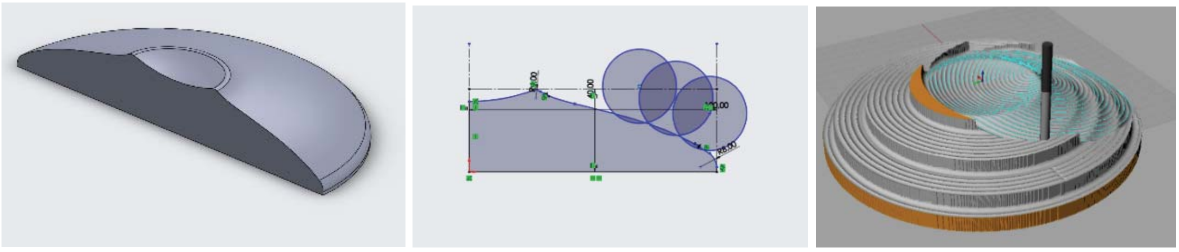


Figure 11: CAD modelling and CAM sequence prepared for the Dip-Casting form.

The plaster mould (in this case the 220mm diameter plaster form) was attached to a piece of pine brandering, to allow it to be held in place and suspended in the ceramic slip bucket. The casting slip was thoroughly mixed while still in the storage bucket. The Plaster form was then lowered into the slip bucket allowing the slip too completely surround the edge of the pattern (figure 12). This allowed for the plaster to then start forming a layer of hardened slip over the form. The plaster form was suspended in the slip for a total of 12 minutes resulting in a wall thickness of approximately 5mm.

Figure 12: Dip casting the plaster form into the bucket of black slip. Barstool for added support.

This was then carefully removed from the slip bucket, and flipped over to allow the clay to continue hardening over the form (figure 13 left image). Initially, the ceramic part was left on the plaster mould to dry overnight. As it dried, the part began to shrink onto the plaster form, resulting in a large crack in the part. For the second attempt the cast was left to rest inverted for only 3 hours, allowing it to harden somewhat, before removing it from the plaster form and resting it on the lip of a large bowl for support overnight. Once leather-hard (the next day) the rim of the part was smoothed using a fettling knife and damp sponge.

Figure 13: Dip cast for removed from positive mould showing surface texture created by cutting bit.

The fact that the mark of the machine cutting bit in the plaster surface is something not to hide, but rather to accentuate, it means that the actual cutting tool can be an interesting aspect of the final design aesthetic. The final form was fired together with the previously discussed 3 part mould spice pots at 1170°C and created a very interesting visual outcome (figure 14).

Figure 14: Final fired dip cast dish.

It is evident that the tooth marks from the cutting bit (6mm HSS drillbit) are able to leave intricate and extremely prominent marks in the surface of the form. It is obviously of personal preference, however the fact that the mark created by the NC cutting sequence is at the centre of the final design aesthetic and allows for the interesting digital handmade aspect of the outcome. If however a perfectly smooth surface is required it would need a more suitable cutting bit, smaller CNC step-overs resulting in a longer cutting time.

8. BENEFITS OF USING CAD CAM WORKFLOW FOR THE MANUFACTURE OF SLIP-CAST MOULDS

- Calculating and compensating for ceramic shrinkages for tolerance specific parts:
  For instance if a ceramic is tested and is known to have a 8.5% shrinkage once fired, the file can be scaled up by the exact factor to take this into consideration. Furthermore if additional moulds need to be manufactured or if a ceramic with a different shrinkage rate is used, then this can be re-manufactured to a more appropriate scale.
- Dependence on CAD accuracy for form reproduction:
  The mark of the craftsman is often desired, however, if the dependence on extreme accuracy and surface finishes is required, then the inaccuracies and human error are undesirable. This allows for the accuracy of the 3D Printer or CNC machine to be the limiting variable.
- Multiple component assemblies:
  With the reliance on CAD Components for the production of the moulds, these components do not have to be singular components, but could be multiple components forming complex assemblies. Again relying on accuracy in the CAD environment and CAD calculated shrinkage rates allows for closer tolerances and more complex products to be manufactured using Ceramic slip-casting.

9. CONCLUSION

Although the ceramic slip-casting process has been utilised for hundreds of years, there are many opportunities for new approaches within the mould making process. This paper illustrates just three variations where experimentation has yielded satisfactory outcomes. There are most definitely many more areas of exploration and striving to incorporate additional aspects of additive and subtractive manufacturing techniques within the field of ceramics and we look forward to constantly pushing these boundaries in attempting to find new and effective cross-overs between the digital fabrication and traditional manufacturing methods.

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