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Three-dimensional Printed Ceramics for Concept Modeling and Bespoke Production

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Abstract. *Many ceramic manufacturing companies use three-dimensional (3D) computer-aided design (CAD) software and 3D printing technologies to produce design concept models for evaluation. Although the value to the design process is limited due to the types of material that can be printed, conventional modeling and processing methods still need to be used to achieve a design concept model in a real material. A solution is desired that delivers a prototype that looks and feels like the final product and which can be fully tested for functionality, glaze, and decoration. In collaboration with Denby Pottery as the industrial partner, this research project has refined and enhanced the 3D ceramic printing process already developed at the University of the West of England, and has enabled the production of concept models of new design ideas in a real ceramic material, printed directly from CAD data, fired, glazed, and decorated. © 2013 Society for Imaging Science and Technology.*
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INTRODUCTION

The Centre for Fine Print Research at the University of the West of England was first introduced to three-dimensional (3D) digital technologies and rapid prototyping techniques during an earlier AHRC (Arts and Humanities Research Council) funded project to investigate photo-ceramic tiles. A subsequent project, again funded by the AHRC, "The fabrication of three dimensional art and craft artifacts through virtual digital construction and output" was used to investigate the use of 3D rapid prototyping and digital fabrication techniques in the areas of Art/Craft and Designer/Maker Ceramics. This project successfully demonstrated that 3D printing with ceramic materials was a viable method for the production of ceramic artworks, and a series of works was produced for several artists. During the course of the project it was realized that there may be other commercial applications for this process. Although the physical properties and characteristics of 3D printed ceramic tableware bodies are not yet comparable with those of ceramic bodies produced by conventional forming techniques, and such bodies would not be able to withstand the rigors of daily use in terms of chip resistance and dishwasher suitability, one area where the process could find an immediate application would be in concept modeling for new design shapes. In collaboration with Denby Pottery, a successful bid application for follow-on funding was made to the AHRC to investigate the viability of using this technology to produce design concept models for the tableware industry. This article will describe the materials and techniques used and show by means of case studies some of the output from the project.

Denby Pottery is one of the UK's most well-known and long-established ceramic manufacturers. The company was founded in the early 19th century and is a household name in the tableware industry. Denby competes in the global marketplace for traditional and contemporary tableware, and is well known for its high-quality stoneware, china, and glaze finishes. The Denby design team is based at the company's factory and headquarters in Denby, Derbyshire. Denby Designers were amongst the first ceramic designers in the UK to make extensive use of 3D computer-aided design (CAD) and rapid prototyping for the production of concept models within the ceramic new product development process. Denby has in-house 3D printing facilities—the company uses the Z Corp powder 3D printing system to fabricate prototype models in the standard Z Corp plaster-based composite material. The standard Z Corp materials allow the designers at Denby to effectively communicate the shape of their designs but not the more subtle material qualities of ceramic, i.e. the weight, tactility etc.

3D CERAMIC PRINTING

The appearance of relatively low-cost 3D powder printers from Z Corp gave rise to the idea that these technologies could perhaps be used to print ceramic artworks. Fundamental to the concept of 3D printing of ceramic powders is the Z Corp 3D printer, and the purchase of a Z 310+ model at the start of the project allowed development work to begin. The Z Corp system uses two moving beds of powder traversed by a carriage consisting of a roller to move a precise thickness layer of powder from the feed bed to the build bed, and an ink jet head that moves north and south on the same carriage. The printer software slices a 3D virtual model into layers 100 μm thick and sends each layer to the print head sequentially; each layer represents a cross section of the model. The ink jet head prints binder onto the powder build bed in the pattern of the layer cross section, the build bed drops down by a layer thickness, the roller mechanism moves across to the feed bed which rises by a layer thickness, the roller then sweeps the layer of powder from the feed bed

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across onto the build bed, and the process is repeated until the model is built. After allowing about one hour for the model to set, the model can be removed from the build bed and the excess powder is removed.

Several research teams have investigated the Z Corp 3D printing process (which normally prints with plaster-based powders) to fabricate ceramics, including the original inventors of the process, Yoo and Cima at MIT.[1] More recently, Hoskins and Huson at the CFPR at the University of the West of England,[2] Balistreri at Bowling Green University,[3] and Ganter at University of Washington,[4] have undertaken research replacing the standard plaster-based composite material with a ceramic body material. Ganter has concentrated on producing a low-cost open-source system to reduce the cost of prototyping in an educational context. Balistreri has used the process to make ceramic artworks. At the CFPR, recent work has concentrated on the potential commercial applications of the process, and techniques to allow thin wall section items to be printed and fired have been developed.

In conventional ceramic forming processes, a clay body is used that is composed of a mixture of different materials that react together to form a fired ceramic. An industrial ceramic body will contain clay minerals which exhibit plastic properties when mixed with water; this allows the ceramic body mix to be shaped or formed into a mold, and provides the green (unfired) strength to the mix. Other components such as feldspathic fluxes are added, as they form a glass-like structure during firing to bind the materials together. The final ingredient is silica in the form of flint or a ground sand that acts as a filler and is vital to obtain the correct thermal expansion of the fired body to ensure a good glaze fit. The selection of different types of raw material and the adjustment of the ratios of these materials in the blend allows the fired characteristic of the final ceramic body to be adjusted.

The type of ceramic body used in this project was a low-fire porcelain-type powder material developed by the research team at the CFPR UWE. An organic binder needs to be dry mixed with the body powder to allow the Z Corp ZB60 ink jetted liquid binder to bond together the ceramic materials prior to firing. The organic binder used was up to a 20% addition by weight of Z Corp ZP15e powder.

The bisque firing schedule used was a ramp rate of 100°C/h to 1200° with a 30 min dwell at 600, 1000, and 1200°C (see Figures 1 and 2).

This firing schedule was repeated for the second bisque fire of the slip-dipped items.

The glaze used was a standard commercially available white opaque leadless glaze fired to 1050°C at a ramp rate of 150°C/h with a 30 min dwell at 1050°C.

Decals used were standard commercial open stock fired to 800°C at a ramp rate of 150°C/h.

Common characteristics displayed by all 3D printed ceramic forms compared to conventionally formed ceramics are that they exhibit a high firing contraction and distortion, a high porosity, and low strength. These disadvantages can be allowed for in the production of one-off artworks, but can cause serious problems when attempting to reproduce a commercially acceptable tableware shape. To reduce the apparent porosity and increase the strength of the final fired piece, a technique of dipping the bisque fired 3D printed ceramic into a slip (a suspension of clay in water) consisting of the 3DP ceramic body with the organic binders removed can be used to improve the surface finish, reduce the porosity, and increase the fired strength.

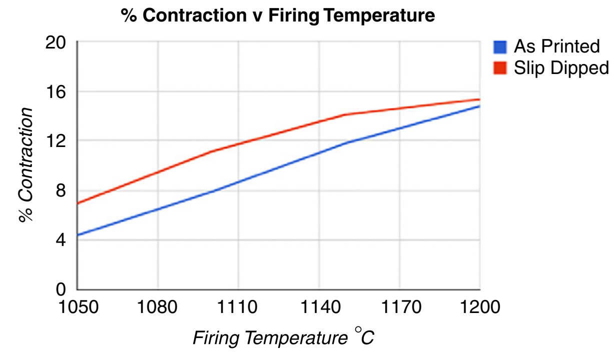

Figure 1. Firing contraction.

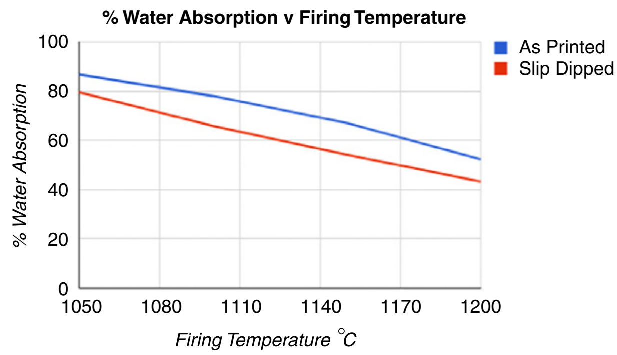

Figure 2. Water absorption.

CONCEPT MODEL DESIGN PROCESS

Tableware and whiteware companies already use 3D CAD and computer numerical control (CNC) models to produce tooling that feeds into traditional mold making methods. Some companies have advanced further and use 3D printing machines such as those produced by Z Corp and Objet to print out 3D visualization design models. The positive model produced from this process can then be used to continue the process by traditional techniques.

The traditional ceramic design method involves transcribing dimensions for a design from a drawing, turning it on a lathe or modeling it in solid plaster, and then turning and adjusting the design as the model develops. From this, a mold is made in potter's plaster from which a slip cast clay model is made which is then fired and glazed. The disadvantage is that this method can be a very slow and labor intensive process requiring a great deal of skill. The model is difficult to alter, and modification often means starting again to adjust the shape. CNC milling uses 3D CAD software to create a virtual model that is then machined using a CNC miller out of a modeling material. The model has a potter's plaster mold cast from it; it is then slip cast with clay and fired. This is a much faster process, allowing the designer to make design iterations, thus speeding up the modeling process. The Z Corp printing method used by Denby Pottery employs 3D CAD software to develop designs, which are directly printed using standard Z Corp material. The design process allows multiple iterations to take place and creates a model with the same shape and section as the final piece, but in a plaster material that cannot be fired or take glaze, decoration, or be tested for its functionality.

3D PRINTED CERAMIC CONCEPT MODEL

Denby Pottery is seeking a concept model process that looks and feels like the final product, which can be fired, glazed, and decorated, and can be fully tested for functionality.

Conventionally, highly vitrified thin section bodies such as bone china and porcelain used in tableware require profile setters during firing to maintain the integrity of the shape. Profile setters are purpose-built ceramic supports that have a similar expansion and contraction rate to the object they are supporting. So, when fired, the body will not warp unduly because it is supported by its profile setter. These support systems would not necessarily be suitable or available for new concept shapes. However, it is possible to use the 3D CAD model to generate custom firing supports for the model that can be 3D printed at the same time in the same material as the model and that will maintain the integrity of the shape during firing (see Figures 3 and 4).

Following are three individual design case studies performed during the project, showing the concept models produced using the above methods.

The first two case studies were undertaken using 3D files provided by the Denby design studio, and the third was an exploration of a concept provided by Peter Ting, a leading design and creative consultant with more than 20 years' experience working in the luxury goods market. He is associated with companies including Royal Crown Derby, Asprey, and Thomas Goode. He is also an advisor and member of Board of Trustees to the UK Crafts Council. His creative practice brings together an understanding of traditional materials and craftsmanship in ceramics, glass, and metal, and a strong interest in new digital technologies including computer-aided design and 3D printing.

Design Case Study 1: Denby Sugar Bowl

One of the first items that the Denby designers invited the CFPR team to make by ceramic 3D printing was a sugar bowl. The shape of the sugar bowl was based on an existing Denby production item. Denby designers added a flower pattern in low relief on the lid and sides of the sugar bowl. The relief pattern would be challenging to make using conventional ceramic forming techniques such as slip casting, because of the difficulty of releasing the item from a mold. However, ceramic 3D printing could potentially make it.

Figure 3. Denby production sugar bowl.

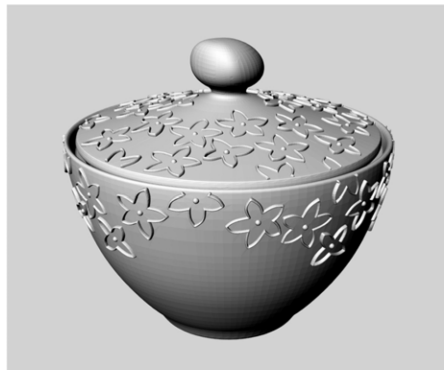

Figure 4. Sugar bowl with flower relief pattern, 3D CAD model.

The sugar bowl and lid were 3D printed in ceramic and then de-powdered and dried in an oven. The sugar bowl and lid were then placed in the kiln to be fired. The results of the first attempts at firing the ceramic sugar bowl are shown in Figure 5. The first attempt at firing the sugar bowl and lid was unsuccessful, because the items were unsupported during the firing process. The 3D printed ceramic powder is held together by an organic binder. As the 3D printed items are heated in the kiln the organic binder burns out before the sintering temperature for the ceramic powder is reached. This means that the 3D printed ceramic items pass through a vulnerable stage when there is no binder present to hold the powder together. At that stage any unsupported shapes are likely to collapse before the sintering temperature is reached.

In order to support the 3D printed items during the firing process, it is necessary to design and make purpose-built setters. Setters are support structures that help maintain the shape of the ceramic item during the firing process. Setters are commonly used in conventional ceramics to maintain the shape of vulnerable items as they are fired, for example, vitreous ceramics with thin sections. When using 3D CAD software, it is a relatively quick and easy process to generate a setter simply by offsetting the external or internal surfaces of the shapes that require support. The designs of the setters for the sugar bowl and lid are shown in Figure 6.

The 3D printed ceramic sugar bowl, together with support structures (setters), is shown in the kiln in Figure 7.

Figure 5. The first attempts at firing the 3D printed ceramic sugar bowl and lid were unsuccessful.

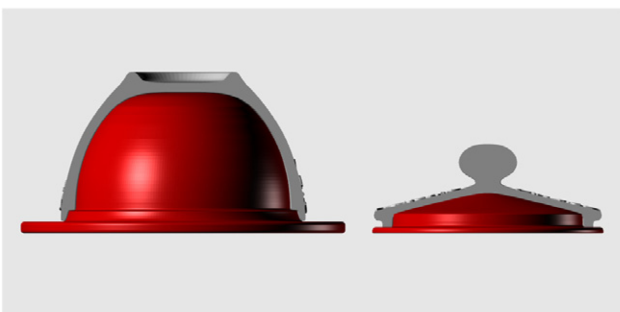

Figure 6. Setters for the sugar bowl and lid, 3D CAD models.

The fired ceramic sugar bowl and lid are shown in Figure 8. Following the first firing, the sugar bowl and lid are dipped in a porcelain slip, as shown in Figure 9. This increases the density of the 3D printed ceramic and improves the surface finish. Following dipping, the sugar bowl and lid are fired for a second time. The results of the second firing are shown in Figure 10.

This case study demonstrates that ceramic 3D printing may be exploited to create a concept model in fired ceramic with low-relief surface patterning which would be difficult to make by conventional ceramic forming techniques. The ceramic concept model was successfully fired and glazed in the conventional manner, as shown in Figure 11.

DESIGN CASE STUDY 2: *Denby Cup*

Denby designers provided the UWE team with a 3D CAD model of a cup that is representative of Denby's typical output. This is shown in Figure 12.

Figure 7. Sugar bowl and lid on setters in the kiln.

Figure 8. Fired ceramic sugar bowl and lid.

Figure 9. Dipping the sugar bowl in porcelain slip.

In order to maintain the shape of the cup during the firing process, it is necessary to create supporting structures or setters that are made from the same 3D printed ceramic material as the piece itself. A 3D CAD model of the cup was used to generate the shape of the setters. The inside surface of the bowl of the cup and the top of the handle were identified as key surfaces which would be supported during

Figure 10. Sugar bowl and lid following second firing.

Figure 11. 3D printed ceramic sugar bowls, fired and glazed.

Figure 12. Denby cup.

firing. Using Rhinoceros (Robert McNeel Associates), these surfaces were offset by 0.5 mm, to allow clearance between the cup and setters. Standard Rhino NURBS modeling tools were then used to construct the setters based on these key surfaces (Figure 13). The 3D printed cup and setters are shown prior to firing in Figure 14.

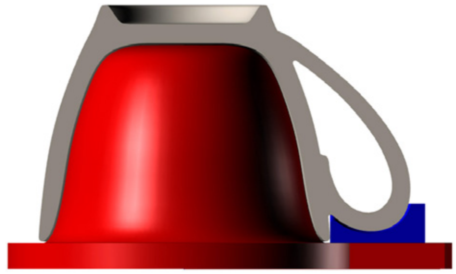

Figure 13. Cross section CAD model showing the cup and setters.

Figure 14. 3D printed cup on setter prior to firing.

Figure 15. 3D printed cup on setter following firing.

Following firing, the cup was removed from the kiln and inspected. Whilst the body of the cup had maintained its shape with minimal distortion, the lower part of the handle, which was unsupported during firing, had deformed, as shown in Figure 15.

In order to better maintain the shape of the cup handle, an additional setter was designed to fit inside the handle to support it during firing. The additional setter is shown in Figure 16. When the cup with new setter was fired, the additional support was found to greatly reduce distortion in the handle, leading to much more satisfactory results. This case study demonstrates that ceramic 3D printing may be employed to fabricate an item of shape and section thickness that is the same as or similar to that of a typical mass-produced piece (see Figures 17 and 18).

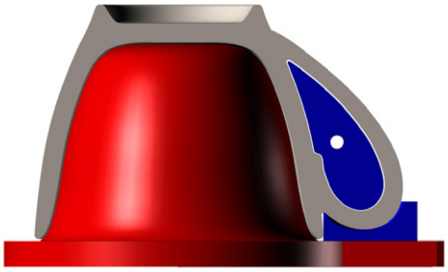

Figure 16. Cup with additional setter to support handle during firing.

Figure 17. Cup and setter with handle support following firing.

Figure 18. Finished bisque fired cup.

DESIGN CASE STUDY 3

Peter Ting Bristol Teacup

Peter Ting expressed a strong interest in working with the UWE team on the development of one or more ceramic pieces, which would be designed specifically to explore the potential of 3D printed ceramics. He proposed several design concepts including the pierced, double walled teapot and teacup designs illustrated in Figures 19 and 20. Both the teapot and the teacup are challenging pieces with design features that would be extremely difficult to reproduce by conventional ceramic forming techniques. After some discussions over the feasibility of realizing the two designs, the teacup was chosen as the design most suited to the ceramic 3D printing process in its current stage of development.

Having selected the teacup as a feasible design for fabrication in ceramic, the next stage of development

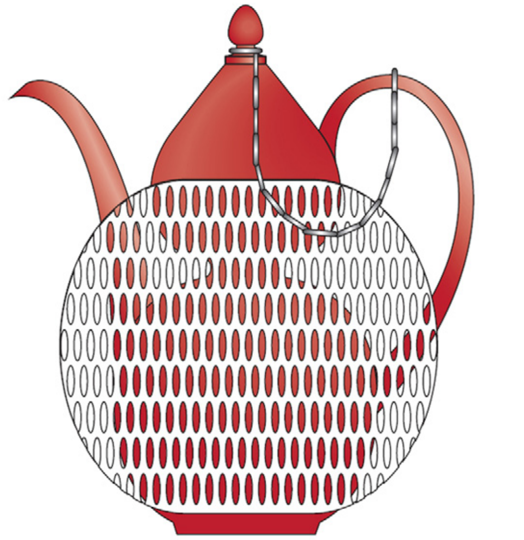

Figure 19. Peter Ting teapot design (2012).

required the 2D design provided by Peter Ting as vector drawings to be translated into a 3D CAD model. The vector file was imported into the 3D modeling software Rhinoceros (Robert McNeel Associates), and the vector curves and lines were used as a basis from which to generate the 3D surface model shown in Figure 21.

At this stage, a minimum wall thickness of 3 mm was assigned to the teacup model, and eight internal ribs were added connecting the inner and outer walls to add strength and to help the structure hold its shape during firing. These features are illustrated in the cutaway drawing shown in Figure 22.

As well as creating the teacup itself, the CAD software was used to generate a solid support structure, which would support the piece during firing. This was achieved by offsetting the internal surfaces of the teacup by 0.5 mm (Figure 23). The teacup and support were built alongside one other in the 3D printer (Figure 24). The 3D printed ceramic teacup, together with support, is shown in the kiln prior to firing in Figure 25.

The results of the first attempt at firing the teacup are shown in Figure 26. The overall shape of the teacup has been reproduced reasonably well; however, distortion, which has occurred during firing, is clearly visible around the foot and in the pierced areas at the front and back of the piece. In order to overcome these problems, it was therefore necessary to modify the design by changing the internal structure whilst maintaining as closely as possible the overall form of the piece.

The minimum wall thickness of the teacup was increased to 4.5 mm, and the number of ribs connecting the internal and external walls of the piece was increased from eight to ten (Figure 27).

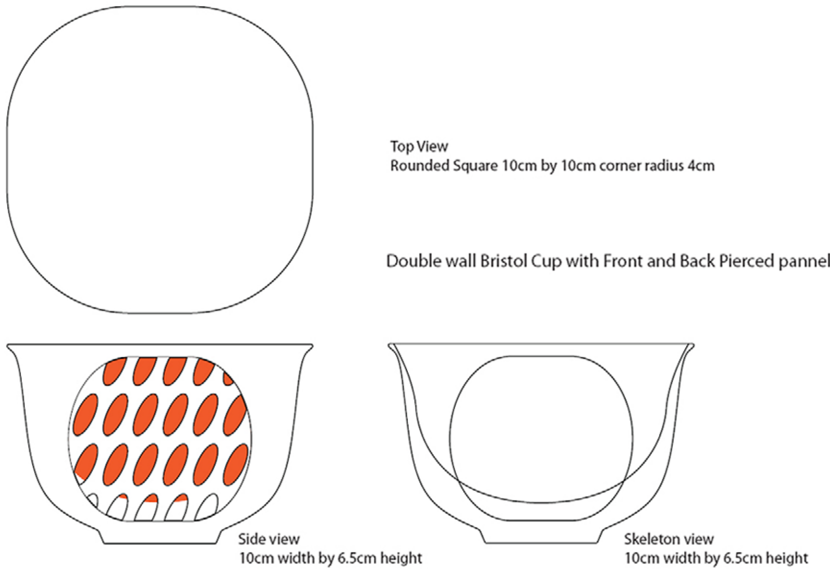

Figure 20. Peter Ting teacup design (2012).

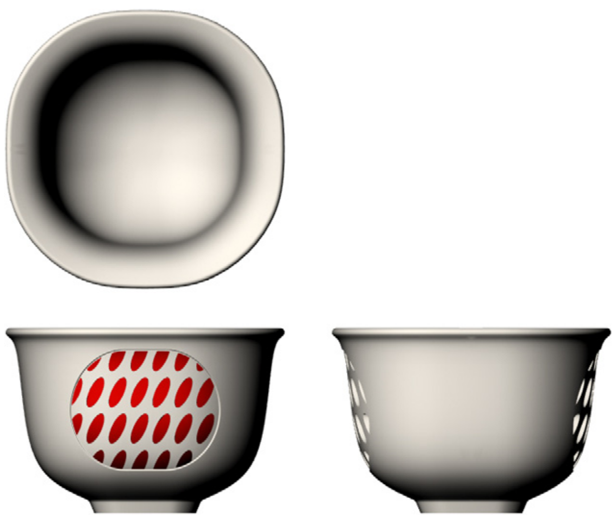

Figure 21. 3D CAD model of teacup created in Rhinoceros.

Figure 22. Cutaway drawing showing double wall design with connecting ribs.

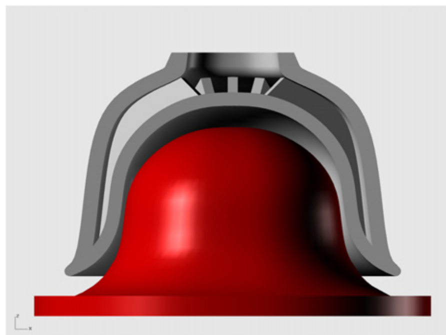

Figure 23. Teacup and internal support structure.

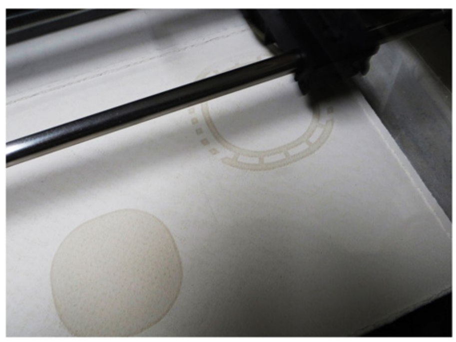

Figure 24. 3D printing teacup and support.

These modifications proved to be successful in maintaining the shape of the piece during firing, as can be seen in the bisque fired piece shown in Figures 28 and 29. The overall shape of the piece has been maintained and the distortion has been reduced to a minimum.

In conclusion, we can state that Peter Ting's Bristol teacup demonstrates that the ceramic 3D printing process can be exploited to reproduce design features that would be difficult to create using conventionally formed ceramics.

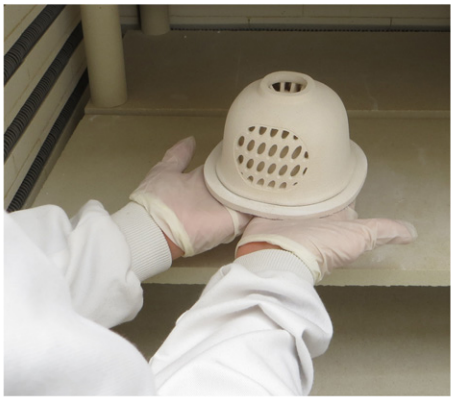

Figure 25. Placing the unfired teacup and support in the kiln.

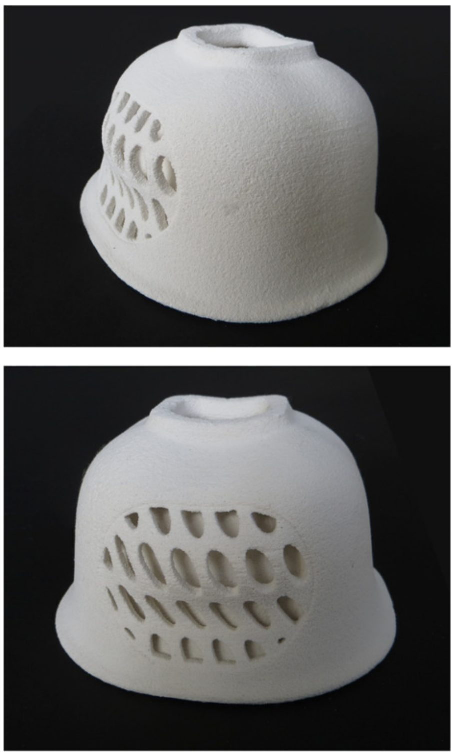

Figure 26. First fired piece showing distortion due to the firing process.

It should be noted that some minor design changes were needed, including increasing the wall thickness and adding extra internal ribs, in order to maintain the shape of the piece during firing. As with all fabrication processes, it is necessary to take into account the particular capabilities and constraints of ceramic 3D printing in order to achieve successful results (see Figure 30).

These case studies provide evidence that ceramic 3D printing has the potential to extend the range of creative opportunities available to artists and designers for the production of one-off and limited edition ceramic pieces including artworks and design objects. There has been considerable interest in the process from both the British design community and commercial ceramics companies including Denby Holdings Ltd., Steelite International, and Dudson Tableware in the UK, and Costa Verde Porcelain in Portugal.

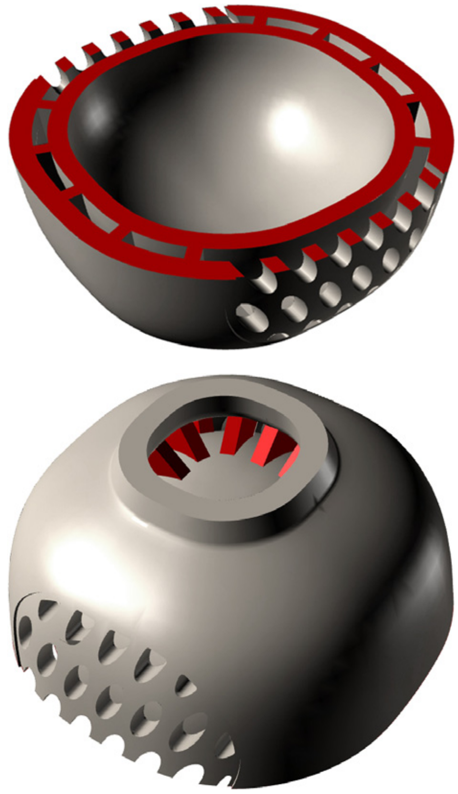

Figure 27. Internal rib structure of teacup.

Figure 28. Peter Ting Bristol teacup bisque fired (front view).

Figure 29. Peter Ting Bristol teacup bisque fired (side view).

Figure 30. Peter Ting Bristol teacup coated in porcelain slip and re-fired.

As well as the examples given in this article, over the duration of the project a variety of ceramic shapes have been produced for both individual artists and commercial designers. Collections of 3D printed ceramics made are on display at the Head Office of the Arts and Humanities Research Council and at the UK Government Department for Business Innovation and Skills. The Peter Ting teacup will be exhibited at the Museum of Art and Design in New York during November 2013. It is estimated that in excess of 50 high-quality finished pieces have so far been produced by the process.

With ongoing research, it is now at the stage of being a viable production process, and CFPR UWE has the intention to set up a spin-out company to offer a commercial bureau for ceramic designers and artists to produce concept models and bespoke artworks.

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