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Reflections on a Collaborative Research Project in Digital Moulding for Glass Casting and Artistic Interpretations

Abstract

This is a two-part paper; firstly, describing a collaborative research project aiming to provide innovation in glass investment casting through the exploration of digital fabrication methods. Secondly, illustrating examples of the artistic exploration of this process alongside digital technologies, such as 3D scanning, in the pursuit of mixed media artefacts. It will therefore compare traditional moulding and construction methods with digital fabrication methods. The paper is written from my perspective as a glass artist with little experience of digital technologies and discusses the impact of the collaboration upon my working methodology and creative output.

This research project was initiated in early 2010 at Falmouth University by Tavs Jorgensen, Research Fellow in 3D Digital Production, and myself, Gayle Matthias, Senior Lecturer in BA(Hons) Contemporary Crafts, both members of Autonomatic, a research group at Falmouth University. The aim of the project is to explore ways of combining my specialist knowledge of kiln-formed glass and Jorgensen's experience with digital design and fabrication technologies.

Previously I collaborated with Aron McCartney, providing a case study for his PhD research into ceramic shell moulding, which had not previously been explored in terms of glass casting. Whilst this technique had numerous significant advantages compared with conventional glass moulding techniques, this method presented a number of technical challenges for users and has so far seen limited adoption by the glass community. The impetus behind our research project was to utilise my knowledge of the ceramic shell process by extending its application and relevance when combined with emerging digital fabrication technologies.

This research has now successfully established an entirely new method of creating glass casting moulds directly from three-dimensional CAD files without the need for a physical pattern. The method developed is based on Additive Layer Manufacturing (ALM) technology using a three-dimensional printer, a process commonly known as 'Rapid Tooling' (RT). The inner part of the mould can be printed on a 3D printer and strengthened by the application of refractory outer layers. Through examples of my creative practice, which employs both conventional and digital methods of mould production, the paper will illustrate a number of unique advantages of RT digital moulding including accurate glass casting, economies in mould production and firing schedules which could have an impact on studio and institutional glass casting production methods. The success of the project has resulted in sponsorship from the sector-leading companies Z Corporation (US) and Gaffer Glass (NZ).

The paper will also reflect on the personal struggles of finding an artistic application/voice for digital tooling, especially with a restrictive digital skillset to draw on. Issues concerning autonomy of production, aesthetic values and relevance to established artistic concepts and material language are discussed. My current artistic practice concerns low-tech construction methods to assist with the exploration of concept over and above the technical process, and so the paper will also address the dilemma of how to use digital tools to help realise and stay true to the original ethos of making.

Introduction

Having been a practising glass artist for over twenty years working predominantly with kiln-formed glass processes, I have witnessed many transitions within studio glass. The movement is fairly young, established in the 1960s in the art schools. Over these years improvements have been made in line with technological advances in glass machinery and equipment and increased availability of wide ranges of compatible glasses. Digital technologies such as water jet cutting, vinyl plotting and laser cutting are commonly employed by glass practitioners. Some processes, however, especially aspects of investment moulding, remain fairly antiquated, resulting in inaccuracies in the moulding process. The research discussed in this paper aims to enhance these traditional moulding methods.

Firstly, I would like to describe an ongoing collaborative research project aiming to provide innovation in glass investment casting through the exploration of digital fabrication methods, comparing traditional moulding and construction methods with digital fabrication methods. Secondly, I will illustrate examples of my artistic exploration of this process alongside digital technologies, like 3D scanning, in the pursuit of mixed media artefacts. The paper is written from my perspective as a glass artist with little experience of digital technologies, and I will discuss the impact of the collaboration upon my working methodology and creative output.

Part I – Collaborative research into digital moulding for glass casting

Conventional moulding

According to Cummings, 'Casting is normally taken to mean the filling of a void within a mould with a liquid form of your material, allowing this liquid to solidify, and then separating the object and mould to reveal the desired form' (1997: 81). Moulds need to be resistant to distortion and cracking, porous and soft enough to allow the expansion of the glass yet able to withstand high temperatures, usually between 850 and 880°C, and be easily removed from the glass after firing. Moulds tend to be made from adapted recipes of plaster and quartz, with additional refractory powders to help resist high temperatures and prevent the mould mixture from sticking to the glass.

Traditional lost wax fabrication for glass casting consists of a series of steps and could be described as a meditative process, Cummings paints a picture of 'generative rhythms' which are 'accumulative through stages rather than single events; this allows for 'opportunities for feedback, revision and adjustment' (1997: 10). I know that within my own practice there is a certain pleasure and reward from such a slow pace of production and opportunities arise through play and 'what if' scenarios. It is the space between making which can be as important as the activity itself. Negatively, it can be perceived as an unnecessarily laborious process going through a series of indirect positive and negative model and moulding stages without coming into contact with the glass. An extended period of courtship is required to become familiar with glass's inherent qualities. These numerous stages can also result in compounded errors in model and mould making which can gradually, subtly remove the glass artefact from the original intention (master model).

Conventional investment moulds tend to fall into two categories: monolithic moulds and multi-layered moulds. The monolithic mould is produced in a single pour of refractory mix over a wax pattern contained within cottling. The multi-layered mould is hand-built in layers, which may vary in thickness and material content and are applied using a brush, spatula or by hand to follow the profile of the wax pattern. For both processes, wax patterns tend to be steamed out of the refractory mould; the abrasive action of the steam can also deteriorate the mould surface.

Thwaites and Seybert at the RCA undertook an investigation and comparison of glass casting moulds in 2002, which featured an international survey of current studio practice, empirical testing and recommendations for improved investment mould recipes. However, the outcomes were still based on traditional silica-based plaster/quartz mixes with additional modifers and they are hazardous by inhalation.

Ceramic shell moulding

The realisation of 'Father and Son' which formed part of my 'Generation' series provided a case study for Aron McCartney's PhD on the adaption of traditional bronze casting ceramic shell investment moulds for glass casting. This introduced more accurate and efficient ways of making investment moulds with vast improvements in terms of reduction in materials, firing cycles and durability. As McCartney describes, 'Ceramic shell moulds are made from liquid slurries. These are based on colloidal silica mixed with molochite flour and stuccos of dry molochite, applied in graded layers to a wax pattern' (2001: 149). McCartney altered this recipe by modifying the initial layers in contact with the glass to prevent the mould mix from sticking and included a softer sandwich layer to accommodate the expansion and contraction of the glass during the firing cycle. The wax pattern is burnt out of the mould using a blowtorch; this also carbonises the inside of the mould. Unfortunately, this process has not been adopted by the glass community, possibly through lack of dissemination, but also due to the subtle intricacies of the moulding process, wax burn out, and drying process which requires specific ambient temperatures and air flow in order to evenly dry the moulds. This can be difficult to replicate in a studio set-up.

Collaborative contextualisation

My collaboration with Tavs Jorgenesn, Research Fellow in 3D Digital Production and member of Autonomatic, a research group based at Falmouth integrating digital skills and technologies in craft practice, sprang from a discussion about ceramic shell moulding.

Tavs Jorgensen originally trained as a craft potter before becoming a designer in the ceramic industry. Recently he has focused his practice on research into the use of new digital design and fabrication tools. Currently, he is involved in projects concerning digitally driven reconfigurable tooling including DIY CNC. The purpose of this collaboration became to combine my knowledge of kiln-formed glass with Jorgensen's experience with digital technologies by the investigation of Rapid Prototype (RP) 3D printing.

Current research in RP modelling in relation to glass casting has focused on the use of 3D printed patterns translated into glass via the lost wax method or burn out of RP models. Direct printing of glass using glass ballotini and glass powders has been researched by companies like ExOne Co and Professor Mark Ganter's vitraglyphic 3D printing research at the Solheim Additive Manufacturing Laboratory at the University of Washington. However, this tends to produce opaque *pate-de-verre* like artefacts, which are fragile and shrink extensively on firing.

According to Cutler, 'While it is possible to directly print objects in glass using an RP machine, as yet, there is no single source or system that can provide all the needs of a glass artist, as 3DP materials and processes remain in experimental mode' (2012: 99).

Research description

Our initial collaborative tests made use of the ALM (Additive Layer Manufacturing) equipment at Falmouth, in this case the FDM (Fused Deposition Modelling) RP machine that produced models in ABS plastic.

The ABS plastic was treated in the same way as a wax pattern and invested in the multilayered ceramic shell with an inner softer sandwich layer. However, on burn out in the kiln, the mould was not sturdy enough to accommodate the expansion of the plastic and cracked. According to Material Safety Data Sheets, ABS plastic fumes are also hazardous by inhalation so these tests were abandoned. We were approached by a Z Corporation 3D printers representative who offered to provide a series of test samples in a starch-based powder as an alternative to the ABS plastic.

Z Corp's ALM technology is based on building parts by spraying binder on layers of powder, a process which has been developed from two-dimensional inkjet printing technology. While we had little experience with this particular ALM technology, we were aware that the Z Corp 3D printers could work with a number of different powders, both inorganic plaster-based and organic, starch-based, compounds (Jorgensen and Matthias 2013: 5).

These starch patterns were fragile to handle during the moulding process, though successfully burnt out using a blow torch without cracking the mould. However, the surface quality was poor. We tried impregnating the starch patterns in hot liquid wax to improve their stability but this was not particularly successful and did not improve the surface quality to any great degree. This led us to test another sample donated by the Z Corp rep in the form of a small vase made from a new plaster-based material (zp150 powder) which we filled with glass cullet and fired. We were impressed to see that such a fragile looking mould could survive the firing cycle, indicating good refractory possibilities and that the glass had taken on the internal form, be it small, without completing adhering to the plaster. This opened up a whole new direction for our research and shifted the emphasis from RP model making and ceramic shell moulding to Rapid Tooling (RT), whereby we could potentially 3D print the mould directly without the need for a physical pattern. The pattern would only exist virtually on the computer screen in the 3D software.

Figure 1. RP test models in ABS plastic and starch. RT mould printed in the zp150 material. Photo: Jorgensen 2010

The RT concept is, however, nothing new in terms of Z Corp technology. The company had for a number of years been selling a refractory build medium called ZCast (3D Systems n.d.), for the creation of moulds for metal investment casting, but the use of this build medium had always remained very limited, perhaps due to a very low surface resolution (Jorgensen and Matthias 2013: 6).

In Rhino software, Jorgensen generated a series of moulds based on the accumulation of random geometric primitives. The random sphere model became the main test due to its complexity of undercut surfaces. Z Corp continued to support our endeavour and RT printed a series of moulds, which varied in wall thickness and composition.

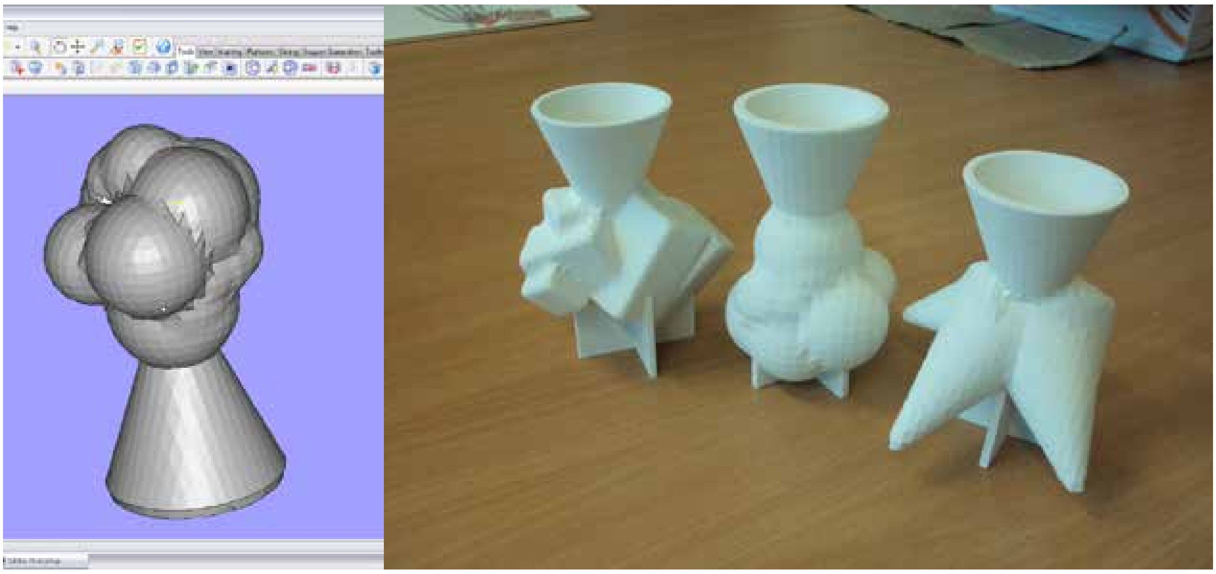

Figure 2. Screen shot and RT moulds printed in the zp150 material. Photo: Jorgensen 2010

The limitations of the RT mould were soon revealed on firing a larger amount of glass in a more complex form. ‘From this series of tests we also discovered that the zp150 would shrink about five percent when exposed to the temperatures needed for glass casting (750 – 800°C)’ (Jorgensen and Matthias 2013: 7). We used a plant pot as a reservoir to store the additional glass needed to fill the mould, so that it would trickle cast. The mould collapsed under the weight of the glass – the precarious nature of the original mould design aided this. However, the surface of the glass in contact with plaster was promising in its clarity and the ease in which the mould would dissolve in water made the demoulding process very efficient, good indicators that the process was worth pursuing and that the addition of supporting refractory layers, the modification of the plaster surface by the application of infiltrants or a combination of both methods were all areas for us to explore.

We returned to the ceramic shell process as a way to back the RT150 powder mould. We created stands for the moulds that also acted as handles that located inside the mould and allowed easy manipulation of the moulds during applications of coloidal silica and molochite stucco. Initial results were shown to representatives of Z Corp who then agreed to sponsor us by providing a Z Corp 310 printer, which was installed in the university in 2011.

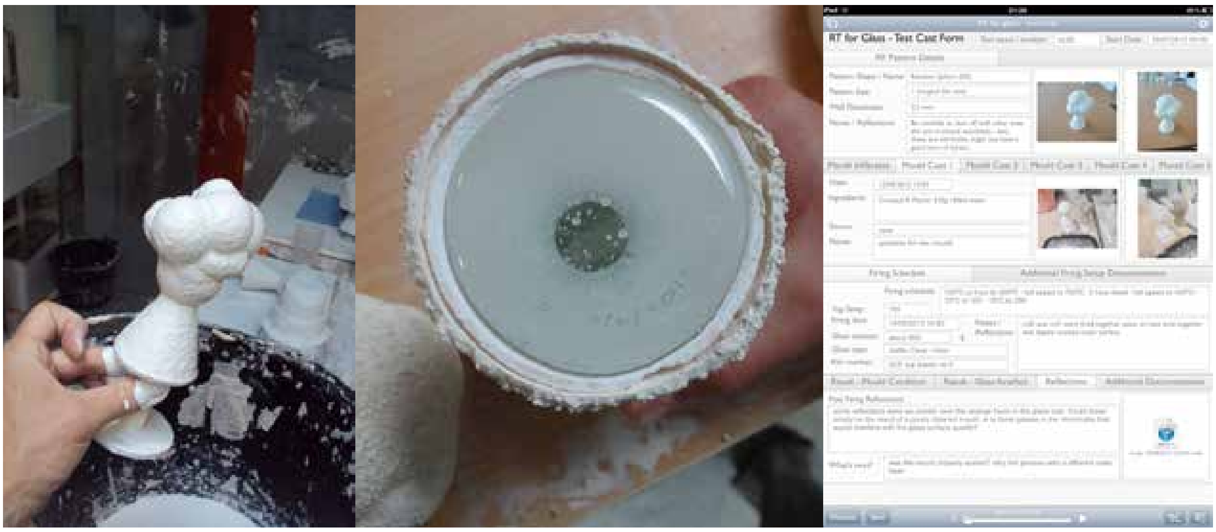

Figure 3. Tests and iPad journal. Photo: Jorgensen 2010

To our disappointment, we discovered a discrepancy between the shrinkage of the RT inner mould and the back-up ceramic shell layers. Ceramic shell is very stable and does not shrink during firing, whereas the 150 powder shrinks quite considerably for a plaster-based medium. We had the powder analysed as Z Corp were not willing to divulge such trade secrets, but we still did not establish the reason for this shrinkage – it might have been due to organic materials burning out during firing. The small gap between the inner mould and the outer shell meant that the inner layer was not fully supported and therefore produced hairline cracks. Pre-firing the plaster inner layer, then applying the shell, was a viable option but seemed to introduce an unnecessary complication to the moulding and adversely affected the economics of the process.

We therefore embarked upon a series of tests to try and reduce the shrinkage of the zp150 powder mould by using different infiltrants, modifying the ceramic shell and testing other supportive refractory layers to see if we could find a match. We did manage to halve the shrinkage rate of the zp150 powder. We tested a wide range of materials with mixed results; testing was accumulative, and in some cases intuitive. We used the collated data to establish the next round of tests.

The necessity of a versatile research journal was recognised, and in an attempt to find a format to compile all the information into complete journal entries we experimented with the use of a private blog. Prior to that, we had tested traditional analogue ways of recording and collating data, but both methods insufficiently captured and contained the diverse research methodology.

In order to facilitate a way of effectively logging our research we developed our own template for a ‘rich media’ journal using a database template for an iPad, which allowed us to photograph, record audio and empirical data so that we could easily reflect upon our analysis. Recorded conversations were particularly useful as they provided a greater context – spontaneous musings on the test results were sometimes insightful. Audio prompts also helped to maintain a research flow, especially on occasions when momentum was lost due to other commitments.

Through basic trial and error, application of prior knowledge, processes of elimination and combined and varying understanding of moulding materials we have successfully managed to marry the RT plaster mould with refractory back-up layers in several different outcomes. Our lack of scientific knowledge has meant that we have experimented through basic questioning of material properties and understanding of basic principles in the manner of creative practitioners, with intrigue, frustration and perseverance.

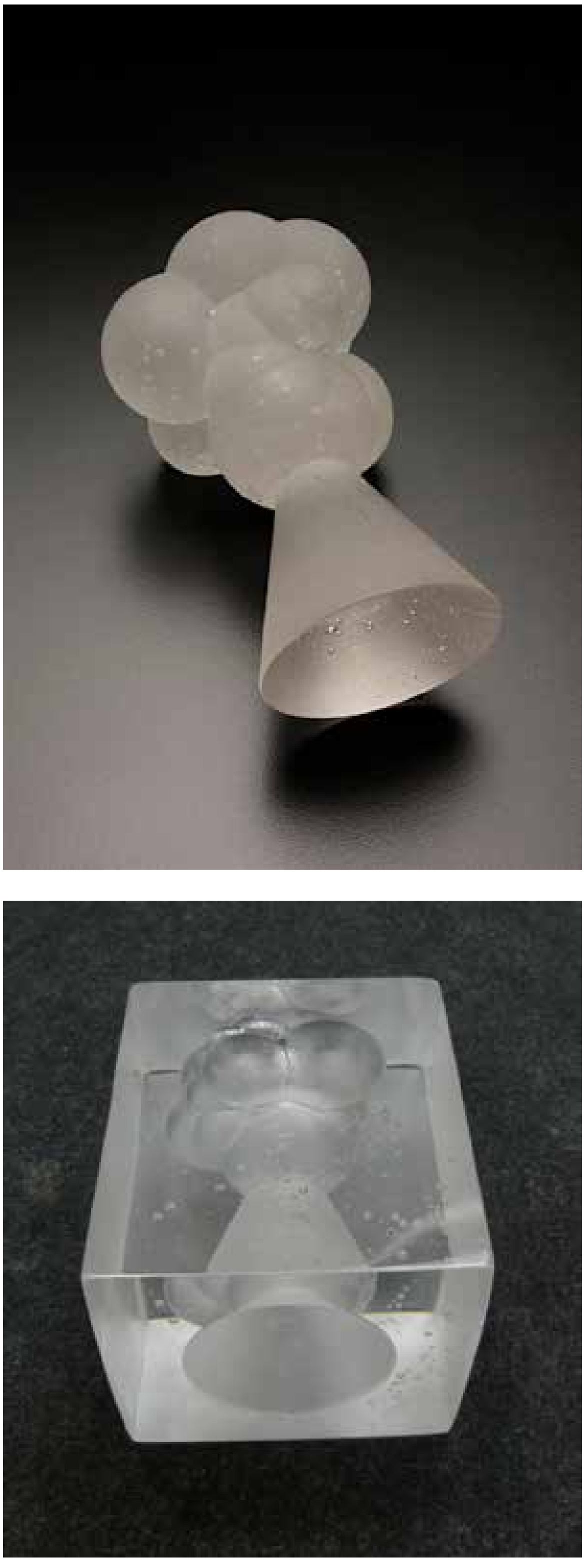

Figure 4. Successful glass casts. Photos: Jorgensen 2010 and Matthias 2013

Advantages of the RT glass moulding technique compared with conventional moulding include:

- New creative opportunities through the use of 3D software
- Very easy transition from virtual files to glass artefacts
- Significantly reduced moulding materials
- Reduced energy use through lower temperature and shorter firings
- Potentially better glass surface quality
- Easier and safer de-moulding
- Safer materials (Jorgensen and Matthias 2013: 10)

We are still in the process of testing the moulding process. Through further testing we want to trial different types of glass. We aim to address issues of scale of the RT mould which is currently restricted by the size of the build chamber, explore extended uses beyond casting, researching other kiln-formed glass processes and other material applications. We are in the process of running a pilot project with undergraduate students at Falmouth to test the moulding process on a varied range of models.

The RT moulding research has clearly defined objectives and as a consequence is a logical, technical series of problems to solve; this contrasts with my personal interpretation of digital fabrication methods.

Part II – Artistic interpretation

Contextualisation of artistic approach

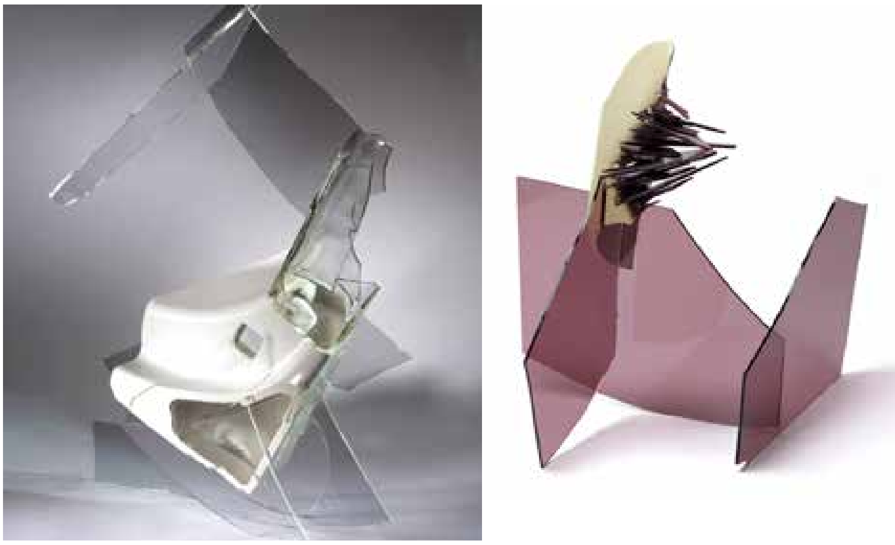

Figure 5. *Anatomical Deconstruction I* and *Anatomical Deconstruction V*. Photos: Simon Cook 2011, 2012

In my current personal work, which does not involve digital fabrication, I am exploring the relationship between materials and the body. I am interested in the element of danger associated with glass, wishing to create precarious and delicate structures supporting utilitarian ceramic found objects to intensify the desire for the audience to physically engage with the work.

The distorted bone-like ceramic element has been deliberately broken to allow the viewer access to internal layers and cavities. Sheet glass is used to extend and redefine forms and reference the movement of the body. The construction of the work is deliberately low tech, using cut and paste methods. My aim is to liberate myself from my technical straitjacket. As Sennet states, 'the craftsman's desire for quality poses a motivational danger: the obsession with getting things perfectly right may deform the work itself' (2008: 11). I seek and strive for imperfection in my work, a 'wilful amateurism'. I struggle to make my work imbalanced, to disrupt and offset a harmonious composition by interjecting an awkwardly cut sheet of glass, lodged into a brutal cut. To allow work to be publicly displayed with a chip or scratch could be judged in terms of poor craftsmanship.

Pye's ethos of 'the workmanship of risk' (1968: 20) is a terminology I would like to apply to my practice, with respect to intentional disparities, the avoidance of precise repetition, where 'rough workmanship does not necessarily imply bad' (1968: 34). 'Against the claim of perfection we can assert our own individuality which gives distinctive character to the work we do', states Sennet (2008: 105). I hope by combining the digital processes with the broken readymade and sheet glass I can maintain this agenda for making so that the digital work can be exhibited alongside the low-tech work in a seamless way.

I perceive myself to be a craftsperson in that I work with the language of glass alongside other materials. I work with techniques of glass manipulation but my work is not about those techniques. Neither do I want my work to be about the digital process. (Unfortunately, this paper does not include a critique/contextualisation of contemporary craft.)

However, as a practitioner, it is important for me to be able to find ways to use RT moulding in my work: to define the limitations of the RT moulding and other digital equipment that support the 3D printing through artistic interpretation, to test whether these processes are appropriate for the generation and realisation of my concepts, to familiarise myself with CADCAM through experiential learning, and to test whether the digital processes are generally user-friendly. With assistance from Jorgensen, recommending appropriate digital software and kit for me to experiment with and providing guidance throughout these processes, I have managed to complete a piece of work and am in the latter stages of production of a second piece which follows similar principles to the first.

Description of my digital interpretation

For my first piece of digitally generated work I had an exhibition deadline to meet, which provided a framework. My work is in part initially a response to ceramic fragments by investigating forms in relation to their broken surfaces. Being interested in edges, where one edge meets another, a cut or broken piece of glass or ceramic, the creation of tension where edges meet, the digitisation of edges naturally became my starting point

Because of my limited CAD skills I did not feel that I could produce CAD models in a conventional way, as I would have to spend many hours getting up to speed with the software prior to being able to make what I envisaged. Instead, the models that I generated had to come from an alternative 'by proxy' method, and with the assistance of Jorgensen and his digital input. Masterton stated that 'it is important for digital makers to know their tools in the same way as any other craft person' (2007: 17), which is true in terms of feeling in control, being efficient in design and production and being able to safely operate equipment and creatively exploit and in some cases redefine its boundaries.

However, if I had known how to use CAD then I might not have discovered this particular way of working which, for me, seems more intuitive and less removed from the material process, retaining physical/haptic engagement. These production methods may be idiosyncratic or significant to other practitioners faced with a similar situation of inexperience of CADCAM. As McCullough observes, 'the more we learn how to do, the less we know what to do', and 'the more sophisticated the techniques, the more people become intrigued by them, and the less anyone cares to focus on other aspects of the human condition' (1996: 67).

Figure 6. Three-dimensional sketch. Photo: Matthias 2011

My intention was to redefine and rearrange broken ceramic forms, using glass to extend and exaggerate anatomical references and to unite the two ceramic forms in a new configuration, creating new points of connection. I wanted the glass form to be a fluid continuation of the ceramic edges. I had to work out the positioning of the ceramic in relation to the shape of the glass and the restrictions of the RP build envelope. I used clay to roughly mock up three-dimensional sketches of compositions as a way of exploring potential arrangements; this helped to identify the orientation of the parts and communication of my intentions to Jorgensen.

My implicit knowledge of glass meant that I was aware of the weight of the material and how it would affect the positioning of the ceramic components, tilting the larger piece of ceramic once assembled. In order to securely fix the glass and ceramics together the glass had to plug into the slip cast ceramic cavity and therefore I made silicone models of the broken edge, by isolating and filling part of the internal space. The forms derived from this process were also intriguing and later stimulated other interpretations of my concept. Broken sections of the ceramic and silicone models of the internal cavity were scanned in a Picza 3D scanning machine. This machine provided a transition between the physical and the virtual object and was a direct way to digitize information. It was not totally reliable as there were some problems with scanning undercut models which affected the accuracy of some of the results and handheld scanners proved even more difficult to operate as they appeared not to be designed to precisely record sharp edges and severe angular shifts.

I focused on the scanned ceramic ends. Using Magics Materialize, I deleted irrelevant mesh faces to isolate the broken surface of the sink. I then had to transfer the information from mesh into splines. In Rhino I drew interpolated splines using the mesh points as guides. The broken ceramic pieces were repositioned on the grid base of a microscribe so that they could be orientated with the microscribe. The microscribe integrated the engagement between objects, materials and the CAD software, a gestural piece of kit that allowed me to capture physical movement and record data. Initially I tried to digitise the edge of the spline directly from the broken ceramic but discovered that the microscribe was not accurate enough. Therefore I recorded the length and width of the internal cavity of both ceramic ends, to create cross-reference points. The curved leading edges of the ceramic were also recorded using the microscribe so that the linking glass form would be an accurate continuation of these edges.

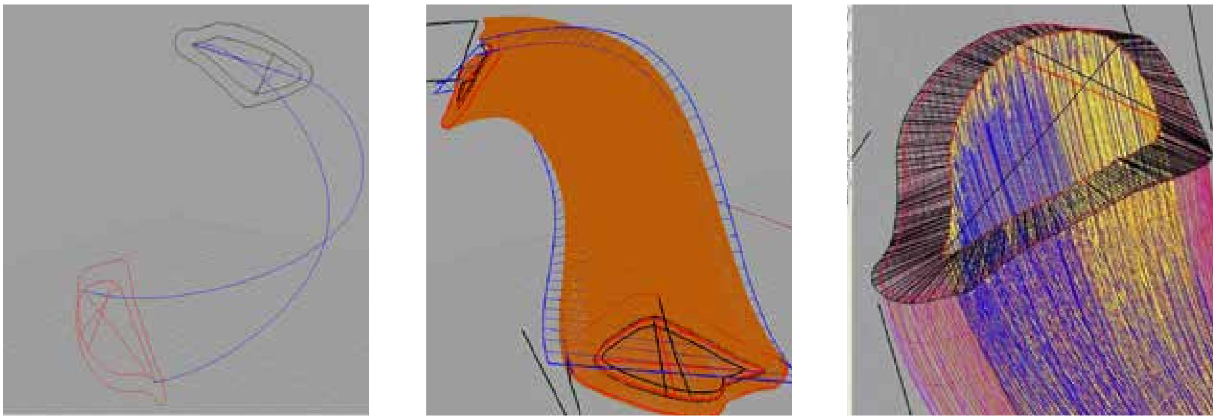

Figure 7. Screen shots of cross-reference points and ceramic outlines, rails, and sweep in Rhino

I could then align and rotate the outline of the ceramic ends with the reference cross, to give an exact positioning. These points were also used to create rails for the sweep so that I could create the surface between the two ends. This raised the question of what arises when these two ceramic outlines are united through the digital process – what form will be revealed through such orientation? I was not in total control of this process on several levels and, given the time and greater confidence with the process, I would have liked to explore other permutations. I found it difficult to work with abstract data, and rotating and orientating the reference crosses did not come naturally to me – I had to keep referencing the actual objects to be able to orientate myself!

More recently on revisiting this process I have annotated dots with a code to correspond with points on the actual object to enable me to more clearly navigate my way around the CAD imagery. In Rhino I experimented with hollow tubes with internal textures as well as solid forms. I required a great deal of assistance with this process. The procedure was akin to learning a new language, but instead of starting with the basics I was thrown into an intermediate class so I learnt particular sophisticated terminology but could not necessarily hold a basic conversation.

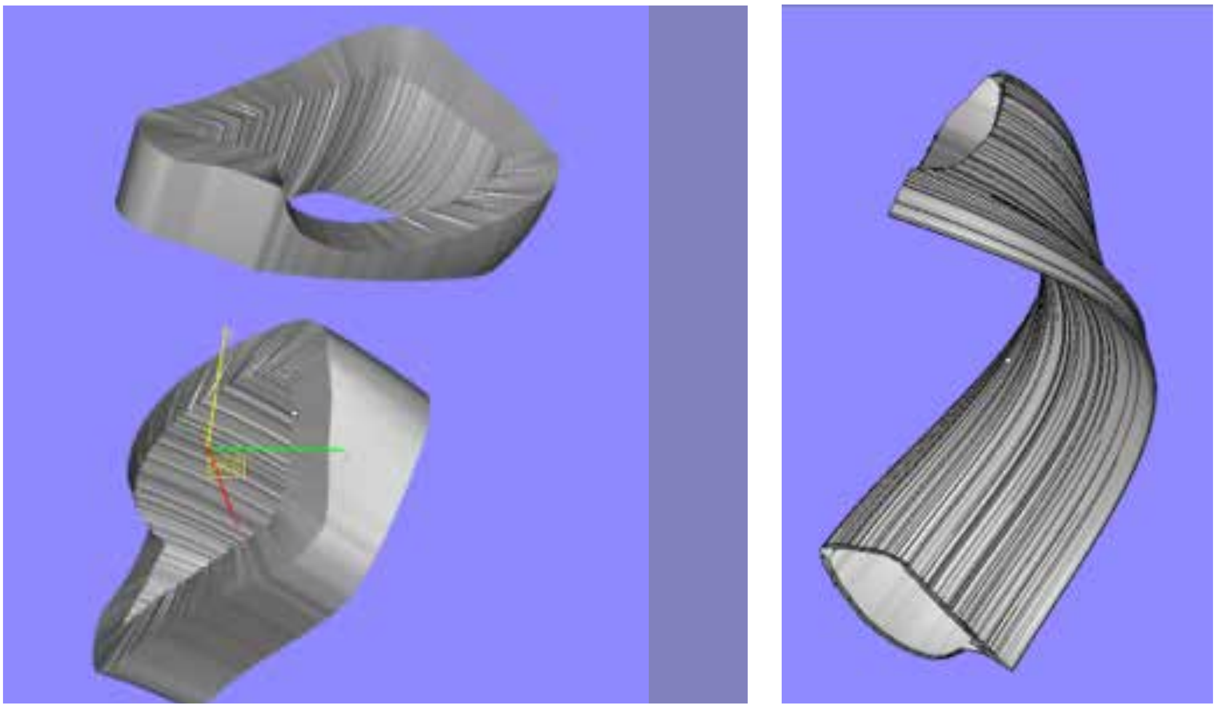

Figure 8. Screen shots of RP printed test ends and textured sweep. Matthias 2011

It was important to bring elements of the 3D CAD modelling into reality on numerous occasions, to check the positioning and physicality of the work. By 3D printing test end pieces and models I was able to check the fit of the components. As Dormer observes, 'one almost comes up against the unexpected in the materials themselves. Materials have flaws and in real life these flaws have to be worked around, but on a computer the material remains imaginary and flawless' (1997: 147). The RP prints have flaws to acknowledge and it is quite easy to lose the subtly of form that needs to occur when one material continues the surface/line of another in a smooth transition.

Unfortunately, there was not the time to experiment with RT moulding methods for this project. Therefore I had to revert to conventional processes: master silicone moulds were taken of the RP model, moulds were filled with liquid wax, a refractory mould was made incorporating air vents and a reservoir and the wax was steamed out of the mould, then filled with glass and fired in a kiln. The internal plug had to be assembled in the wax stage.

The cast was ground and polished prior to assemblage. This re-established a physical engagement with the work and could possibly be the case if other practitioners were to employ RT moulding. The fine linear nature of the digitally printed surface can easily be removed through coldworking the glass, if required.

Figure 9. Sinew. Photo: Simon Cook 2011

Reflections on the artefact – is it a hybrid or intermediate?

Does this work communicate my concept, satisfy or enhance my making requirements in the way I intended it to? Being pragmatic, I recognise this as a transitional piece of work, which I feel does not possess the impact which I attempt to achieve in my low-tech assemblages – it is too precise and predictable in form. There are qualities within the work and the production of the work that are unresolved, partially due to my limited CADCAM skill set, but I was also compromised by the restricted timeframe and as a consequence I was still resolving some model and moulding problems through conventional means. However, this is quite often the scenario when producing work for exhibitions.

CAD can result in a disconnect through delay and separation from the physical relationship of thinking and making and I struggled with this. I still maintained control of the 3D modelling but, due to my reliance on Jorgensen's assistance, I did not have the luxury of playing with forms in a way that I would do with materials at hand. Therefore I had to plan in advance my intentions, then adhere to that decision even if at a later date I felt like I would like to have returned to stage one of the design process. That is not to say that I did not have to revisit stages of the digital processes on many occasions, but this was due to digital technical oversight or missing data or inaccuracy of 3D modelling. In my opinion, the screen shots and production methods are visually more exciting than the finished work, and I have taken inspiration from this and the moulding of internal cavities, which has led me back into conventional casting methods.

Ironically, the finished glass cast element is visually akin to a piece of hot-formed glass, though it would not have been possible to achieve this level of precise fluidity and accuracy of fit through hot glass modelling.

Moving outside my comfort zone is important so that I don't stagnate as a maker, so that I can relate to and be reminded of what it is like to be an apprentice, to throw something fresh into the mix of making and regain an alternative perspective on my practice. On the other hand, the enticement of technique is something that I consciously want to avoid. As McCullough states, 'the possibility of craft lies not so much in the technology as in the outlook you bring to it' (1996: 271).

I would like the exploitation/exploration of these digital tools to help me enhance the glass casting process by arriving at more innovative forms, be they more complex, intricate or basic than I am currently able to achieve by hand. This requires greater knowledge of 3D software. As McCullough argues, digital technology has a lot in common with craft production methods: the use of tools, manual dexterity, employing kinesthetic and visual thinking and experiential learning and that a symbiotic relationship should be actively pursued. Pye refers to the 'workmanship of certainty found in quantity production and in its pure state in full automation' (1968: 20). I have yet to achieve this, and as Pye goes on to state, 'although the components may be made by the workmanship of certainty they will still nearly always be assembled by the workmanship of risk' (1968: 34), which I still find to be the most challenging aspect of my creative practice.

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