

NEW APPROACHES IN GLASS INVESTMENT CASTING - CREATIVE PRACTITIONERS RESEARCHING AND INNOVATING IN THE FIELD OF DIGITAL FABRICATION

ABSTRACT

This paper describes a research project aimed at delivering innovation in a combined sphere of digital fabrication and glass investment casting.

The project has established an entirely new method for creating glass casting moulds directly from three-dimensional computer files without the need for a physical mould pattern, by using a moulding approach based on Additive Layer Manufacturing (ALM) technology.

While the paper includes a narrative of the development of the moulding process, the central argument of the paper is rooted in the project's research/innovation methodology. This argument concerns our profile as creative practitioners and the impact this position has on the research/innovation scenario. Also central in this argument is the use of 'emergent methodologies' (Bolt, 2007) and 'reflective practice' (Schon, 1983). A new type of rich media enabled research journal to aid the use of these methodologies was developed as a part of this project and is also presented in this paper.

KEY WORDS: RAPID TOOLING (RT), ADDITIVE LAYER MANUFACTURING (ALM), USER INNOVATION, REFLECTIVE PRACTICE, RESEARCH JOURNAL, EMERGENT METHODOLOGIES.

INTRODUCTION / CONTEXT

THE RESEARCHERS' PROFILE

A key argument of the paper is based on our position as creative practitioners explicitly using our tacit knowledge of materials, making processes and digital design technologies to undertaking research and innovation in the field of digital fabrication.

This field could previously have been seen as the preserve of specialist engineers or material scientists, and it is our contention it is our perspective and approach as creative practitioners that enabled us to contribute with different perspectives, knowledge bases and approaches in the innovation process and thereby providing a key foundation for the success of the project. Consequently it is highly relevant to briefly outline our background as a part of the context for this research.

Matthias has a long career as a glass artist and university tutor in contemporary craft practice. Jorgensen initially trained as a craft potter before becoming a designer in the ceramic industry. Latterly Jorgensen has focused his practice on research into the use of new digital design and fabrication tools but integrates this work with an active creative practice.

The scope of the project emerged out of fairly open-ended technical and creative explorations, gradually becoming more focused in response to test results and discoveries. Although Matthias had experience with the ceramic shell moulding technique, which in large parts was the 'technical inspiration' for the project, both materials and processes used in the process of trying to solve the technical challenges were left 'open to change' in response to the test results. Such an approach could be termed as an 'emergent methodology' - a phrase which has been used to describe the characteristic qualities of practice-based research undertaken by artists and designers (Bolt, 2007).

CONTEXT – DIGITAL FABRICATION AND ADDITIVE LAYER MANUFACTURING

The field of Additive Layer Manufacturing (ALM), and digital fabrication in general, is currently undergoing rapid development and growth. While these are technologies that artists, designers and other creative practitioners have long explored the *use* of, technical innovation in this sector has largely been the preserve of the *manufacturer* of the machinery and technology rather than the *users* of it.

However, this situation appears to be changing. A number of pioneering projects have emerged in the last few years which are helping to enable and inspire independent innovators from a wide range of backgrounds to make an increasingly significant impact on this field.

Of particular significance is the RepRap project from University of Bath lead by Dr Adrian Bowyer (Jones et al., 2011). This project, aimed at exploring kinematic self-reproduction has resulted in the development of a simple and very affordable Rapid Prototyping (RP) machine. The technical principle of the RepRap use the same Fused Deposition Modelling (FDM) concepts which is employed in commercial RP machines produced by Stratasys (Stratasys Inc, 2012). These machines all use a heated nozzle to extrude plastic filament (usually ABS plastic) to build parts via a

standard ALM principle.

Crucially, the RepRap project has made all plans and software code available for everyone to access and use freely under an open-source licence (Raymond, 1999). As a consequence the RepRap project has been extraordinary successful in enabling individual innovators to operate in the field of digital fabrication. Drawing on this freely available open-source knowledge, a fast growing cottage industry has emerged with many individuals developing their own derivative RepRap designs, known as 'Repstraps' (Jones et al., 2011, p.188).

While the RepRap project has been one of the most visible projects in terms of widening the opportunities for independent innovation in digital fabrication, other projects such as the MACH3 (Newfangled Solutions LLC, n.d.), Arduino (Arduino, n.d.) and Processing (Fry and Reas, n.d.) are also contributing with powerful and low cost tools which enable individual innovators to operate with increased ease in this sector.

While taking inspiration from projects such as RepRap, our project concerns a different ALM technology using a powder based 3D printing technology developed by ZCorporation (3D Systems, n.d.). Our project differs further as does not concern the manufacture of finished parts (as is the case with RP), but is instead based on the 'Rapid Tooling' (RT) concept. Broadly speaking RT is an approach where moulds are made via ALM technologies for the use in subsequent manufacturing processes. The RT approach is currently far less explored than RP, but as a concept holds significant potential as it enables the use of process and material knowledge established in conventional manufacturing processes to be utilized in new contexts.

Apart from this project, glass casting via the RT approach has seen very little exploration and no established procedure or commercial system has so far been established.

CONTEXT – GLASS INVESTMENT CASTING

The general process used in glass investment casting has changed little over many decades with most practitioners relying on traditional casting processes based on the use of bulky moulds made of a mixture of gypsum plaster and quartz. Heating such moulds requires high levels of energy and the quartz powder used in this moulding method is hazardous if inhaled. Despite these drawbacks, little innovation has taken place in this area of glass artefact production.

The few projects which have explored alternative moulding techniques include Thwaites & Seybert (2002) and McCartney (2001), the latter investigating glass casting through the use of the 'ceramic shell' moulding – a technique which has long been an established process for metal foundry applications. The ceramic shell technique is based on creating moulds by applying a series of refractory layers on a

wax patterns (patterns, which are subsequently removed by a 'melting' or 'burning' out – a process known as the 'lost wax' approach). The mould layers are created by using a ceramic slurry based on colloidal silica (Silica Sol) mixed with fired, crushed ceramic granulate (Molochite). This creates thin but strong moulds that have significant advantages compared to conventional glass moulds of plaster and quartz, particularly in regard to lower energy use in the firing process, and also shorter firing cycles.

However, despite these advantages, this technique has to date seen little use. Matthias worked with McCartney on his research and has explored the technique independently in her own creative practice.

PROJECT NARRATIVE

The initial phase of the research was focused on exploring what we had in terms of in-house ALM equipment at our college, which at the time constituted a single Stratasys FDM machine. Jorgensen had previously undertaken experiments with the use of FDM parts for bronze investment casting with ceramic shell moulds. The process of using ceramic shell with FDM patterns is also based on a standard 'lost wax' approach and is well documented having been developed by other researchers (Winker 2008). However, to our knowledge this process had never been explored with glass as the investment medium and this was therefore an obvious starting point for our project.

We started our investigation with a series of tests with FDM patterns created in ABS plastic. These tests quickly exposed a problem with this particular combination of processes and materials. The issue appeared to stem from the special composition of the ceramic shell coating that is needed for glass casting - a composition which had been developed by McCartney (2001). McCartney established that in order to accommodate 'coefficient of thermal expansion' of the glass, a modified ceramic shell layer (different from that used in metal casting) had to be used in order to create a 'softer' shell that allowed the glass to contract in the cooling phase without developing cracks. We found that this 'softer' shell composition would inevitably develop cracks during the burn-out stage of the RP patterns, as this weaker mould shell was simply not strong enough to contain the thermal expansion of the ABS plastic during the heat ramp before the final 'burn out' stage occurred.

Figure 1. (inserted here)

While still undertaking experiments with FDM parts, we were approached by a sales agent for ZCorporation (ZCorp) 3D printers. This particular ALM technology is based on building parts by spraying binder on layers of powder, a process which has been developed from standard two-dimensional inkjet printing technology. While we had little experience with this ALM technology, we were aware that ZCorp 3D printers could work with a number of different powders, both plaster-based compounds and organic, starch-based materials. The starch-based powder was our initial focus, as we expected that this material could replace the FDM patterns in the lost wax approach, potentially without the problems of the material expanding and cracking the ceramic shell moulds during the heating ramp. Sensing the potential for an equipment sale the agent supplied us with a number of test parts built from our three-dimensional files in order for us to trial the concept.

Using the starch patterns did resolve the cracking problems which we had experienced with FDM patterns; however the surface of the starch models was of much lower quality than the FDM made parts. Furthermore, the starch models were also very fragile, making them difficult to handle in the moulding process. These issues were remedied to some degree by impregnating the patterns with hot wax, but these initial tests still indicated to us that this approach had limited real-life potential due to the low surface resolution and a delicate moulding process.

However, as well as supplying the starch patterns, the ZCorp agent also supplied a small test piece (in the shape of a little vase) which had been created in a newly launched build medium. This medium, the zp150 powder, had just been introduced by the company and featured a very high surface resolution. We processed this small sample packed with glass shards through a standard glass casting cycle. The test piece emerged visually unchanged after the firing, and the glass had melted to a small billet in the base of the vase.

Figure 2. (inserted here)

This result indicated that the zp150 build medium had reasonably good heat resistance capabilities. And while not intended for the creation of refractory moulds, (but as a general build medium to produce a wide range of prototypes) it appeared, indeed, to be perfectly suited to this application.

Encouraged by this result we were eager to proceed with further rounds of tests with this material, however the moulding concept with these tests had to be altered from the 'lost-wax' approach we had taken with both the FDM and the ZCorp starch patterns. With the zp150 material we had to take the approach where we would be printing the mould directly with the 3D printer, thereby eliminating the need for

creating a physical mould pattern. The mould patterns would only be virtual representations in computer modelling software. As previously mentioned, this process is commonly known as 'Rapid Tooling' (RT).

The RT concept is, however, nothing new in terms of ZCorp 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.

Relaying the result of the initial glass casting test back to the ZCorp agent generated a significant level of interest and the agent agreed to sponsor a further collection of test pieces created in the zp150 powder. We designed this range of test pieces as RT moulds with wall thicknesses ranging from 2 to 6mm. The forms for these pieces were created as clusters of geometric primitives (cubes, spheres and cones) using the 'Grasshopper' (Davidson, 2012) generative scripting facility in the Rhino 3D modelling software (Robert McNeel & Associates, 2012).

Figure 3. (inserted here)

Casting glass in these RT moulds exposed serious limitations with the concept. We discovered that while the zp150 material had some refractory capabilities, the material would lose much of its strength during the firing and the moulds would fracture and collapse under the weight and pressure of the molten glass. We concluded that the reason for the success of the initial test with the vase shape was likely to be the small size of the piece and geometric integrity of the round vase form. From the 'follow-up' series of tests we also established that the zp150 would shrink about 5 percent when exposed to the temperatures needed for glass casting (750 – 800°C).

Figure 4. (inserted here)

While this cycle of tests exposed some distinctive limitations with the concept, there were also a number of indicators which encouraged us to continue with this particular line of exploration.

Firstly, while the zp150 material only appeared to have had limited structural integrity during the firing process, we expected that the material's refractory capabilities could be enhanced with coatings, infiltrates or other methods.

Secondly, glass cast against the zp150 material seemed to have a better surface quality compared to that achieved with a conventional glass mould made of plaster and quartz. Furthermore, we discovered that RT moulds made in the zp150 material

would dissolve when immersed in water, making de-moulding much easier than with conventional moulds. Equally, if we could make the standard zp150 powder work for this RT process, the versatility of a ZCorp 3D printer unit would be greatly enhanced, as a single machine could be used for both prototyping (RP) and tooling/moulding (RT) without a change of the printing powder being required (using build mediums such as starch or ZCast requires a complete clean out of the machine, which in practice means that users are unlikely to change build medium very often).

In many ways this stage of project could be characterised as the point where our work changed from a relatively open-ended exploration to a much more focused and targeted investigation. Our initial explorative inquiry had served as the provider of the core concept for a potential innovation in glass casting, but also exposed the technical challenges we had to overcome to successfully establish this new moulding process.

We continued with further tests, trying various ways of strengthening the moulds with outer refractory coatings, drawing mainly on Matthias' knowledge of the ceramic shell technique. While still not achieving 'ideal' moulding methods, some of these experiments did result in some fairly successful glass casts.

We presented these casts along with a description our research at the Time Compression Technology (TCT) show in Coventry in October 2010 (the TCT show is widely recognised as one of the main ALM industry events in Europe). During the show we met with ZCorp's chief executive, John Kawola, who recognized a significant business potential in our approach and offered to sponsor a ZCorp 310 printer to our project to facilitate further development of concept.

We took delivery of the machine in early 2011, a development which enabled us to ramp up our investigation significantly as we were now able to print our own test moulds in-house and experiment freely with the technology.

Figure 5. (inserted here)

While it had been a relatively easy process to establish the core concept and create some reasonably successful test casts with simple small forms, developing a robust method which could be used with a wide range of geometries and sizes proved a much more challenging task.

Strengthening the zp150 with a standard ceramic shell coating was an initial obvious approach to resolve the zp150 material's loss of strength during the firing process. But with this method the shrinkage rate of the zp150 material posed a challenge, as a standard ceramic shell coating has virtually no shrinkage when exposed to glass firing temperatures. This incompatibility resulted in a gap between the inner zp150 layer and the outer ceramic shell coating. While the moulds would generally still

remain structurally sound during the firing, this gap would cause small cracks in the surface of the zp150 inner layer, as it was not fully supported by the outer ceramic shell coating.

This shrinkage incompatibility issue remained the greatest challenge in our research and to the success of the concept. Consequently, solving this issue became the main focus for the next stage of our research.

While we were fairly certain that the zp150 powder largely consisted of a variant of gypsum plaster ($\text{CaSO}_4 \cdot \frac{1}{2} \text{H}_2\text{O}$), the exact material composition of the powder was unknown to us. Tests we undertook confirmed that the characteristics of the powder were broadly similar to that of plaster, but when we fired the material we observed that it had an unusual high shrinkage rate. An obvious step was to ask ZCorp to supply us with the composition details of the zp150 powder, so we could identify which compound(s) caused this shrinkage. However, the company made it clear that while they were happy to support our research, the powder composition remained a closely guarded industrial secret, as the company's business model is based on the sale of consumables rather than on the 3D printer hardware.

Without the complete knowledge of the zp150 powder's composition we had to find a way to reduce or eliminate the shrinkage of the compound, potentially by the use of infiltrates or coatings. In an attempt to achieve this objective we undertook a series of material tests and experiments. We were partly successful in this task, discovering ways of reducing the shrinkage rate of the zp150 material to 2 - 3%. But in order to make this 'inner' mould layer fully compatible with subsequent strengthening layers, we still had to find or develop a refractory coating with a compatible shrinkage rate.

In this search we undertook tests of a wide range of refractory materials and compounds. In several cases we found materials that would have the required shrinkage rate, but only during the drying stage rather than the firing stage. For each set of tests we had to develop new approaches and 'theories' about how we could solve the problem. We considered that the solution could be achieved in a number of ways, either based on mineral compounds, or alternatively achieved by an organic/mineral mixture - where shrinkage would be caused by the organic matter 'burning out' during the firing. A solution could also potentially be provided (or partly provided) by a particular way or sequence of applying certain materials.

Throughout the process of developing this research we frequently had concerns about our background as creative practitioners as a suitable qualification and training to undertake this kind of research. We frequently questioned ourselves if professionals, such as engineers or material scientists with far greater theoretical and scientific knowledge to draw on, perhaps would have a greater potential to be successful in this research and innovation scenario.

During parts of the investigation we did seek assistance from a science-based team at a neighbouring university, who carried out analysis of some of the compounds. While very approachable and helpful we found that the scientists' theoretical knowledge to be so specialized that it was difficult to draw solutions from their expertise to our particular challenge as the task appeared to span several knowledge spheres including: mineralogy, silicate and polymer chemistry, and crucially, all applied in a very 'practical' workshop context. Essentially the solution we were aiming for had to be a process that would extend or improve on the existing moulding techniques for glass casting, and theoretical knowledge was only relevant if it could lead to a practical, and very usable, solutions for this application.

To compensate for our limited theoretical and scientific knowledge, we drew heavily on our practical experience of materials and processes - a comprehensive 'library' of tacit knowledge which we had built up over years of creative practice. Just like Schon's (1983) descriptions of how practitioners would construct their *own* theories in order to respond to unfamiliar situations and challenges (and specifically within the context of these situations) we too, continued to develop our own hypotheses and theories in response to the 'feedback' we had from our practical tests, or as Schon describes it: *'a reflective conversation with the situation'* (1983).

In this project, our limited knowledge of scientific theories may also have given us other advantages as innovators, as through our 'ignorance' we were perhaps more likely to explore a wider range of solutions and materials to solve the challenges that we encountered. An illustration of this point could perhaps be drawn from the diverse range of materials we experimented with in our investigation, which included: PVA glue, corn flour, fishing tackle equipment, plastic bags, soil additives, paints, as well as a wide range of more conventional minerals and compounds.

Many of our tests were complete failures or led to 'dead-ends' but others did provide unexpected and promising outcomes, and now (after three years of project development) we finally have achieved a combination of materials and processes which is very close to a highly promising RT method.

The method we have established enables glass practitioners to create a thin 'inner skin' mould on a ZPrinter using the standard zp150 powder, with virtual forms created with 3D digital drawings. Shapes can also be recorded via 3D scanning existing objects and using these files as the virtual mould patterns. The RT moulds are then post-processed using a number of coatings and processes to create strong, but also thin refractory glass moulds. For practitioners who may not have their own ZPrinter (which is likely to be a large majority), numerous ALM bureaus are available to print mould parts on demand.

The list of the potential advantages of the RT glass moulding technique compared with existing methods includes:

- New creative opportunities through the use of 3D software to create forms
- Very easy transition from virtual files to glass artefacts
- Significantly reduced moulding material use
- Reduced energy use through lower temperature and shorter firings
- Easier and safer de-moulding
- Safer materials
- Better glass surface quality (in some cases)

The potential advantages of the process in the context of ALM/ZCorp technology includes:

- Easy transition from RP to RT
- Works with all current ZCorp 3D printers - no need for retro fit
- Utilizes the zp150 standard building medium - no need for specialist binder or build medium
- Applications beyond glass, such as metal alloy investment casting
- Very low cost materials

We are still in the process of undertaking full usability tests of the process, and have not yet released the method for general use. Equally, we are currently considering whether to exploit the process commercially or disseminate the knowledge to other practitioners via an open-source or Creative Commons¹ licence, thereby enabling other practitioners to build on our research and improve the method that we have developed.

RECORDING THE RESEARCH DATA

Recording this research project presented a particular issue in terms of logging a variety of data, not only the results from empirical material tests but also the recording of our on-going reflections on the research, which we consider an a particularly important aspect to capture.

Initially the research was recorded entirely through paper forms, with 'boxes' for recording numerical details of shrinkage rates, mixture compositions etc. While we did include spaces to record comments and reflections, it was a challenge to find a way that could combine these records effectively. Comments and notes became increasingly scribbled all over the forms and we had to conclude that this approach was a largely unsuccessful way of recording (and retrieving) data from our research. Equally, throughout the project we carried out extensive photographic recording of test results (and the research process in general) and looked for ways of linking these

digital images with the tests notes and reflections. We recognise the potential of a well functioning research journal, as highlighted by Gray & Malins (2004), and in an attempt to find a good format which could compile all the information we gathered into complete journal entries, we experimented with the use of a private weblog (blog). While also recognising the importance of recording both the empirical data and reflections as close to the source as possible, we had to concede that the 'messy' environment of the plaster workshop where we undertake most of our practical research was badly suited to computer laptop use. This situation therefore limited the usability of the blog to record the data significantly, since the environment forced us to use an office away from the practical research to log the recordings. We quickly we found this arrangement to be time consuming and 'too separated' from the 'research coalface', and as a consequence our use of the blog soon petered out.

THE DEVELOPMENT OF A RICH MEDIA RESEARCH JOURNAL

As the description above indicates we struggled throughout large parts of the project to find a good format for a research journal which could facilitate a comprehensive capture of all the various data sources in an easy to use format and, crucially, within the actual research environment. However, recently we have been exploring a method which is showing great promise in fulfilling this need. The method is based on using the 'Filemaker Pro 12' (FileMaker, Inc, 2013) database building software. Filemaker Pro is by no means a new application, and using such database software to record and organise research is also an established practice, but what presents new opportunities with this latest release of the software is the linked IOS app: 'Filemaker GO' (Apple Inc, 2012). This free app enables the use of databases developed with the 'Pro' version of the software on IOS devices such as iPhones and iPads.

For us a critical aspect of the software is that it enables the creation of media 'container-fields' within a database template. Such fields can be used to record a wide range of rich media such as images, movies, audio or even finger drawn sketches. This mean that we can now record our reflections as audio (or video), alongside the numerical data we collect from the tests results, data which can be further backed up by images, sketches and movies.

An equally important feature is that fields for textual input recorded either via the on-screen keyboard (or the voice-to-text software SIRI) will expand to take unlimited number of words. Consequently notes can have an unlimited length without 'spoiling' the template structure of the database entry - unlike the paper-based forms we first employed.

In developing this approach we took inspiration from the notion of the 'thick description' – a concept first defined by Geertz (1973) in the field of anthropology. It is a way of recording multi-layered data to explain not only central observations but

also the wider context of these observations. In the same way our aim is to establish easy-to-use templates that enable a multilayer recording of the research using rich media input.

The use of an iPad or iPhone as the input device is also a critical aspect of the usability of this research journal system. These devices are very easy to have to hand at all times during the research, and with a protective case can be used in messy environments - such as our plaster workshop.

Figure 6. (inserted here)

CONCLUSION

It is important to highlight that this project is still in the initial 'invention' phase of a complete innovation sequence (the commercialisation or dissemination phase is still to come).

However, even at this early stage of the innovation sequence we believe that some conclusions can be drawn.

To our knowledge this project is the only university research project which ZCorp has ever sponsored, and we consider it to be significant that the company should choose to support a project from a University which is based on creative practice rather than one from a science based institution. We believe that this provides indicative evidence of the value of creative practitioners undertaking research and innovation using emergent methodologies.

Many authors on innovation highlight the importance of external or independent 'actors' in the innovation scenario, or as Pursell states: '*almost per definition new products, processes and attitudes must come from outside the status quo*' (1994, p.38).

As creative practitioners (and not engineers of digital fabrication equipment) we consider that our 'outsider' knowledge played a key part in the research and innovation process. Such a notion is also highlighted by authors on innovation theory such as Smith (2005). Equally, this research has throughout the project been guided by our needs and knowledge as *users* of technology. Such work is described by Von Hippel (2005) as 'user innovation' – a concept which appears to be increasingly evident particular in the field of digital fabrication and we believe that projects like ours will increasingly be the source of innovation in this field.

Finally, it is worth considering that in some ways this project concerns two innovations. While the primary innovation is focussed on the glass moulding method, the development of the Filemaker Pro database template and the method of using

rich media to combine quantitative research data with reflective practice, we view as an innovation in its own right. This method, which was created as a response to the specific needs for recording the data of the main project, we believe could be a significant tool in assisting the work of other practitioner-researchers, and thereby contribute to increased use of the emergent methodologies. Methodologies which we consider to have played such a significant part in the success of this project.

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Figure 11. Successful glass cast, presented at the 2010 TCT show. Photo: Jorgensen 2010

Figure 12. Using our rich media research journal via an iPad (with a screen shot of an journal entry on the left). Photo: Jorgensen 2010

¹ <http://creativecommons.org/>