Chapter 3: 3D printing introduction and contextual review

The aim of this chapter is to provide an introduction to 3D printing and to contextualise this research project within the field of materials and process development for 3D printed art and design.

Section 1 of this chapter provides a general introduction to 3D printing along with a more detailed description of the two processes used in this research: paste extrusion and powder binder 3D printing, including the capabilities and limitations of these two processes. Section 2 of this chapter will present a review of 3D printing materials and process development in creative arts, industry and research contexts.

There are many sources available that provide information about the different types of 3D printing techniques, compatible materials and the capabilities and limitations of each process. This information is mostly focussed on 3D printing in non-ceramic materials and so falls beyond the scope of what was feasible to include in this research, for further reading refer to, Hoskins, (2014), Warnier and Verbruggen, (2014) and Lipson and Kurman, (2013).

Section 1: 3D printing introduction

What is 3D printing?

3D printing is the general term given to a group of additive manufacturing techniques. Additive manufacturing can be defined as the process of fabricating objects from 3D computer aided design data by selectively depositing, fusing or solidifying materials, usually layer by layer. Other names for 3D printing include rapid prototyping, rapid manufacturing, additive layer manufacturing, freeform fabrication and desktop manufacturing. These terms however are losing popularity in favour of the more general term “3D printing”.

Fundamentally, a 3D printer uses information from a virtual, computer generated model to build a three-dimensional part. First of all, the virtual model is sliced into 2D layers to be printed one on top of the other. The printer then sequentially adds and bonds successive layers of material. Each layer is a cross section of the object, stacked one layer on the next, until the object is completely fabricated. After the printer has finished, objects are removed and post-processed. This usually involves cleaning the part to remove un-used material or structural supports, by de-powdering, washing or in some cases machining the object. Depending on the build material, parts may be infiltrated (e.g. with resin) or sintered to high-temperatures to provide further strength.

Other manufacturing techniques

As opposed to additive techniques, subtractive methods such as cutting, grinding and milling all involve the removal of material from a solid block to obtain a desired shape. Mass manufacturing techniques, such as injection moulding or die-casting require the use of moulds or tools to make the final product. Although casting is arguably an additive process, the method used to create the mould or die is usually subtractive. Additive techniques differ from these as they do not require the use of part specific moulds or tools, and so can be very versatile in terms of what they can produce.

Advantages of 3D printing techniques

Generally speaking, 3D printing techniques are capable of producing parts with geometric and material complexities that would very difficult or even impossible to produce using subtractive or other traditional manufacturing techniques. A subtractive manufacturing tool such as a milling cutter always needs a clear path to access the area which it is about to work on, which means that there are many limitations in terms of shape with these methods. For example, 3 axis CNC (computer numerically controlled) milling cannot create some complex internal geometries or overhanging sections. For 3D printing techniques, the object is fabricated layer-by-layer and any complex interior structures can be constructed at the same time as the exterior. Injection moulded or die-cast parts must be removable from the die or mould in which they are made and therefore parts must be designed in such a way to enable their removal. For simple parts this generally poses no problem. However, as the complexity of the part increases, so too does the cost and complexity of the mould tool and past a certain point, parts cannot be manufactured at all, or must be broken down into a number of smaller components that then require post assembly.

3D printing methods are particularly well suited for applications where multiple iterations of a design or product are required, such as in prototyping applications or for producing customised goods. Subtractive techniques generally require multiple manual or machining operations and the use of moulds, dies or other tools to produce parts. These processes are generally better suited to large volume production where the cost of cost of tooling is amortised over the production run.

Unlike subtractive techniques, most 3D printing processes produce less material waste and often unused material can be reclaimed and re-used [Reeves, 2012]. This is due to material only being added where it is required, rather than cut away in excess.

Disadvantages of 3D printing techniques

Although 3D printing techniques have the potential to produce objects that are geometrically complex, such objects must be supported and held in place on the bed of the machine during the 3D printing process. Without such support~~s~~, there is a limit to the shape of the object which can be fabricated.

For most 3D printing techniques, support material is either added intentionally or as an inherent part of the process. For techniques that use a powdered build material, the un-used (and therefore un-bound) powder acts as a support as the object is being built. Once the part is complete, the un-bound powder is removed, and the resultant object is revealed. For other techniques, the support is often generated in a secondary material which is later removed once the part has been built. These techniques require the use of multiple nozzles to deposit the secondary support material. Finally, some techniques generate support structures from the build material itself, which is then cut or machined away once the part has been built.

3D model generation

It can be argued that there have been many additive processes in existence throughout history such as bricklaying and welding, however these techniques all lack the automation through the input of digital information. This is what sets 3D printing apart from historic additive processes. All 3D printing techniques start with the creation of a computer or digitally generated 3D model. This can be generated either using a 3D scanner that maps the shape of an existing object, or by modelling an object from scratch using Computer Aided Design (CAD) software. Additionally, it is now possible to download 3D models from file sharing sites such as Thingiverse [MakerBot 2015], a 3D design community for discovering, sharing and printing 3D models. Alternatively 3D printed items such as jewellery and ornaments may be purchased from online bureau services such as Shapeways and i.materialise that have a virtual marketplace of digital models.

A 3D model file is typically converted to an STL (stereolithography) file, which has become the standard format for 3D printing processes. The conversion to STL translates the object's form into a mesh surface. The mesh is made up of thousands of interlocking polygons, with each polygon in the mesh holding information about the objects shape [Lipson and Kurman, 2013] When the STL file conversion is complete the model must be checked to ensure that there are no holes or gaps in the model, a property known as being 'watertight'. A watertight STL file must have a surface mesh that accurately and completely covers all surfaces, curves and interior hollows present in the model. An STL file that is not watertight will cause problems when it comes to printing, because it becomes impossible to compute the volume of space and the material requirements. A water tight model is then able to be 'sliced', or decomposed into successive cross-sections, to be reproduced by the 3D printer. The sliced file is used to prepare machine instructions to control the print mechanism and deposit materials. The final stage before printing the model is to upload or communicate the machines instructions to the 3D printer~~s~~, which executes the commands and fabricates the object.

Applications

Applications for objects made using 3D printing techniques continue to grow. An industry that was once known as rapid prototyping has extended its reach to a broader, more diverse range of applications [de Beer, 2013], including such diverse areas as medical devices, aerospace components, fashion, furniture, animation and special effects, and the visual arts.

The growth of 3D printing applications has been accompanied by a growth in the user group of 3D printing technologies. Once used mainly by high-tech organisations and industry, 3D printing is now used on a much wider scale by small businesses, hobbyists and other individuals. The Wohlers report is a leading annual research report undertaken to analyse trends in the 3D printing industry and to find out what 3D printing is being used for. Figure 30 shows the industries served by additive manufacturing for 2012. For that year consumer products and electronics were the industry leaders (20.3%) served by 3D printing processes, followed closely by the motor vehicles sector (19.5%). Medical and dental has established itself as a strong sector for 3D printing and it has been the third largest sector for the past 11 years [Allison and Scudamore, 2014]. Aerospace is the fourth largest sector and it grew from 9.9% in 2011 to 12% on 2012. The 'other' category includes a wide range of industries including oil and gas, non-consumer sporting goods and other industries that do not fit into any of the named categories. Figure 31 shows how organisations used additive manufacturing in 2012. This survey shows that additive manufacturing was being used for direct part production (19.2%) more than anything else.

Figure 30: Pie chart showing the industries served by Additive Manufacturing [by K. Nash – adapted from pie chart shown in Wohlars Report, 2012]

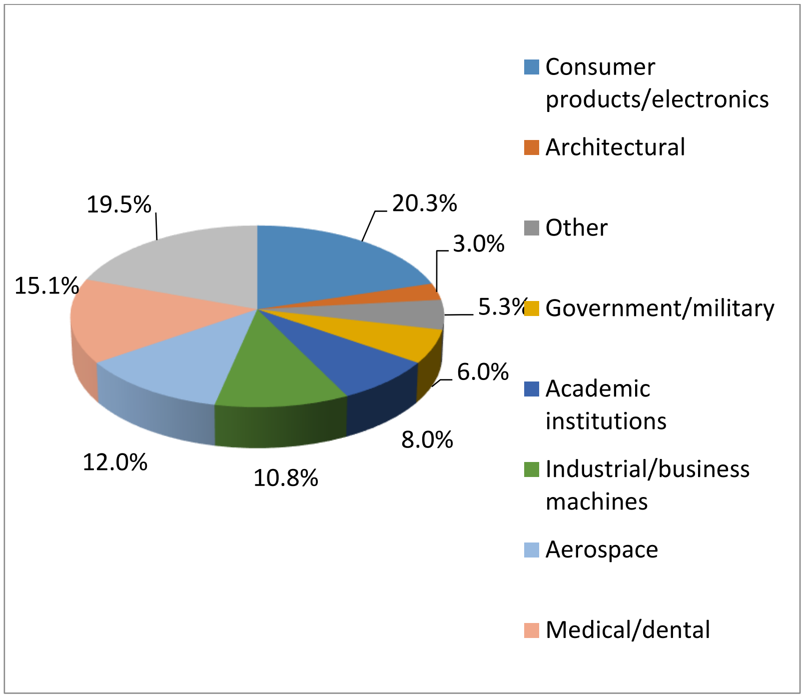
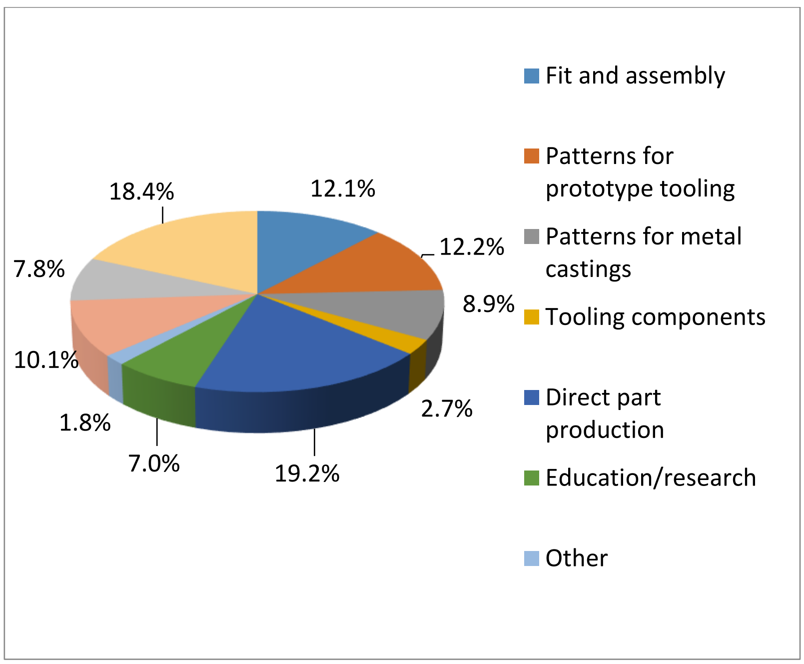


Figure 31: Pie chart showing the range of applications for Additive Manufacturing [by K. Nash – adapted from pie chart shown in Wohlars Report, 2012]



Process description: Powder binder printing

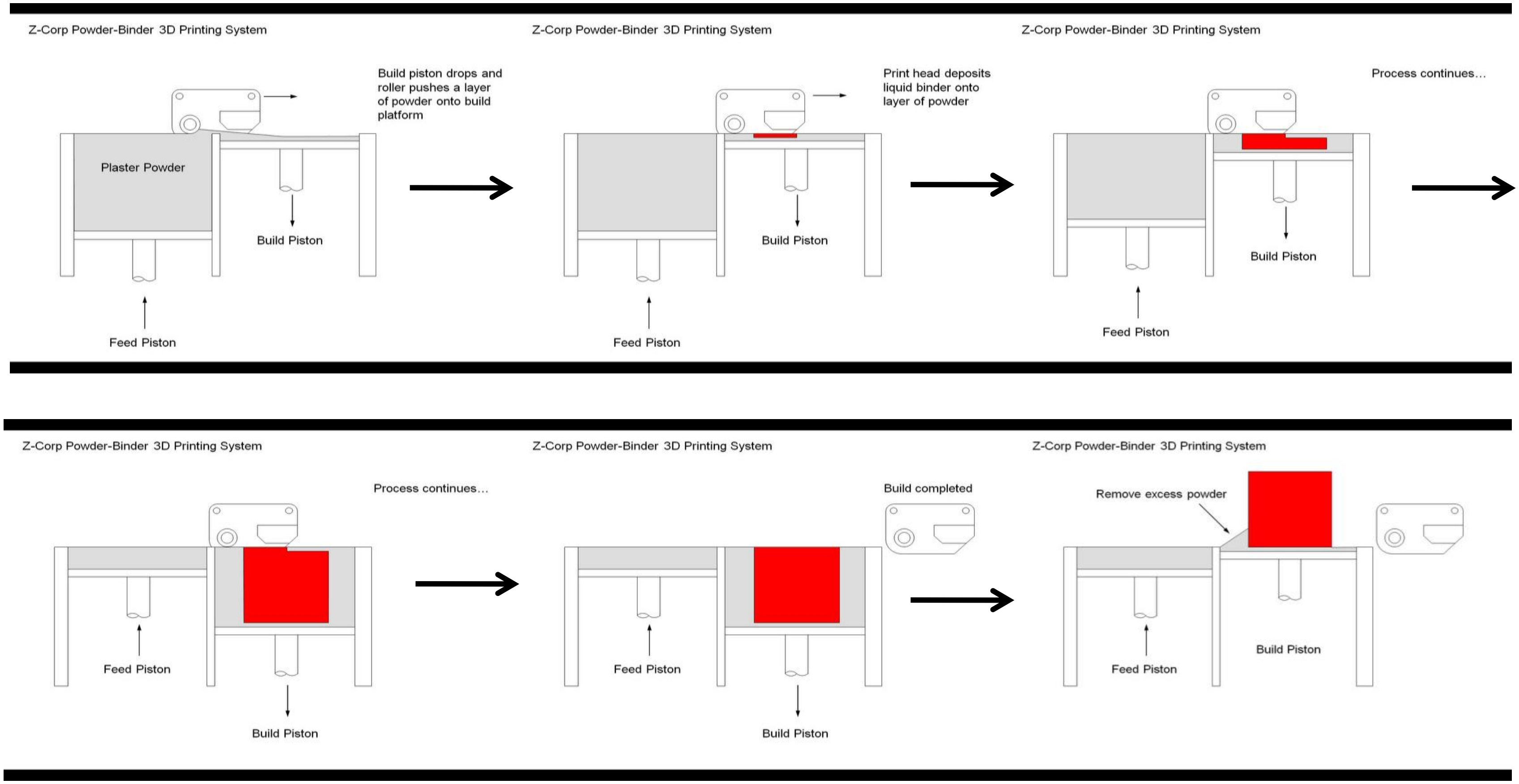
A special section in this chapter is dedicated to powder binder printing as it the primary fabrication method used in this research.

Powder binder printing was developed in the early 1990's at the Massachusetts Institute of Technology (MIT) by Michael Cima and Emanuel Sachs [Wang, 1999]. It was later licensed to Z Corporation, which is now part of 3D Systems. 3D Systems are a major supplier of powder binder 3D printers which they supply for use with a plaster based material. The fabrication process of powder binder printing shall now be described. The printer has two platforms, the feed platform containing the supply of powdered material and the build platform, where the object is to be printed. A roller pushes a thin layer of powder from the feed platform to the build platform. Next, a water-based liquid activator is jetted by an inkjet print head directly on top of the newly deposited layer and a cross section of the 3D model is laid down. The liquid activator reacts with both the plaster material and a binding agent in the powder. Once the cross section has been printed, the feed bed then moves up a step and the build bed down a step to compensate for the change in powder levels. This process is repeated until the 3D model is complete. The un-bound powder supports the object whilst it is being built and can be re-claimed and used in subsequent builds. See figure 32 for an illustration of the process.

In addition to plaster, the supplied material also contains powdered sugar and cellulose which act as a binding agent. In this process the liquid activator jetted by the print head is composed mainly of water which dissolves the sugar in the powder and then sets hard. The cellulose in the powder acts as a mechanism to draw water through the material to ensure the water fully penetrates the object. In this plaster based system, the water-based liquid activator also reacts chemically with the plaster material, liberating heat through crystallisation, resulting in the hardening of the hydrated plaster. 3D Systems supply several models that are capable of printing in multiple colours. These printers have multiple ink-jet heads, one each for the clear, cyan, magenta, yellow liquid activators (binders). In the same way as a desktop colour inkjet printer, the binders are mixed in varying ratios to create a full colour spectrum. Objects produced using this binding process tend to be more fragile than parts produced using techniques that fuse or melt material. Therefore, it is common to infiltrate parts with resins as a post processing step, which not only makes them stronger but also dramatically improves the colour saturation. In recent years there have been a number of research and development projects that have set out to broaden the material options for powder binder printing. Most notably of these have been the attempts to 3D print in ceramic materials, however glass [Klein et al 2015] cement [Gibbons, Williams, Purnell and Farahi, 2010] and sugar [Walters and Huson and Southerland, 2011] mediums have also been explored.

Figure 32: A schematic of the Powder binder 3D Printing process

[Image credit: By Dr Peter Walters (2012), with permission from Walters, P. (2015)]



Ceramic powder binder printing

Using ceramic materials for powder binder printing requires a similar process to the one used for the plaster based system. The main difference when using ceramic powders is that the liquid jetted from the print head does not react chemically with the ceramic particles in the way that it does with the plaster material. Instead, the important thermally induced chemical reactions for the ceramic materials occur during the firing stage. The use of powder binder systems for the production of ceramic parts can be separated by the binding system used in each process. This research uses a water-based binder (similar to the plaster based system) that dissolves sugar and cellulous that are mixed in with the ceramic particles. Other systems use polymer coated ceramic [silica] particles and a solvent-based binder which dissolves the polymer coating to temporarily bind the ceramic particles together. Voxeljet, is commercial supplier of 3DP machines that use a solvent-based binding system, however for this process, the parts are not fired but are instead used as industrial sand casting moulds.

Water-based binding systems

The practical section of this research project uses a water-based binding system and a commercially bought Z Corp. 3D printer (now supplied by 3D Systems). In the vast majority of cases, other research and commercial enterprises use Z. Corp printers as the machine does not require any adaptation to make it suitable for the printing of ceramics. This system uses a powdered binder that is mixed in with the ceramic particles. The binder consists of maltodextrin (sugar) which is dissolved by the liquid activator and sets to provide strength to the ceramic part and cellulose to draw the liquid activator through the powder. The ink-jet head deposits a layer of the water-based binder onto the ceramic powder which is drawn through the material by the cellulous and dissolves maltodextrin. The build chamber is usually heated to assist in the drying and subsequent hardening of the object as it is being built. Once built, the object is heated in an oven to around 70°C for at least 24 hours before it is handled, de-powdered and then fired in a kiln. Once in the kiln (at around 300 degrees) the binder begins to burn out, leaving behind the ceramic materials. The body can be designed so that as the binder (that is holding the whole form together) burns away, fluxes in the body become active and the body starts to vitrify. Once fired and depending on the application, the part may be dipped in a ceramic slip and/or glazed to improve mechanical strength and surface appearance. Both of these treatments require subsequent firings when using standard 3D printable ceramic bodies.

Capabilities and limitations of powder binder printing

The powder binder process is capable of producing objects with a good degree of fidelity and resolution. The resolution of features is limited to the size of the particles in the powdered build material which is usually in the region of 80µm. Other limiting factors include the resolution of the inkjet print head and the layer thickness. Objects are supported during the fabrication stage by the un-bound powder, which can be very beneficial when producing intricate or thin walled sections. In terms of build material composition, this process has greater flexibility over some other 3D printing methods (such as paste extrusion) as there are fewer material requirement during the build stage. The major requirements of powder binder 3D printing are 1) that the particles stick together 2) the powder must flow freely without clumping for proper spreading with the roller and 3) the particle size should not be below 35µm as this can lead to the build-up of static charges in the build which can also result in the material clumping together. The use of a suitable binder ensures that particles stick together during the build stage, minimal inclusions of clay components reduces the risk of the material clumping or spreading poorly and an awareness for component partial size enables sub 35µm particles to be avoided.

A range of particle sizes can be beneficial to reducing porosity, however this is not essential.

Material requirements such as a good degree of plasticity or a particular fluid behaviour does not apply to the powder binder process in the way that it does for 3D paste extrusion, therefore there is the potential for a greater range of compositions to be explored with this process.

A limitation of the powder binder process that applies to all powdered build materials, is the inherent porous structure created by the process. This is mainly caused by a lack of mechanical pressure forcing the particles together during object fabrication, which results in a loosely packed, porous structure. For ceramic powder binder printing this is emphasised by a lack of plastic components and water in the process. The combination of these two components in conventionally formed pottery bodies ensure that they clay particles remain closely packed together during object forming and firing so that porosity is kept to a minimum in the resultant body.

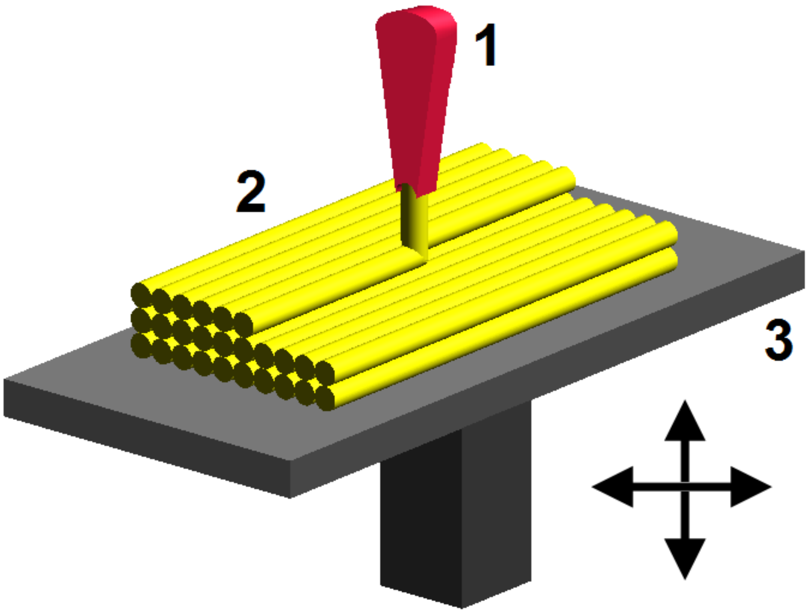
Additionally, objects fabricated using powder binder techniques exhibit poor strength compared to the same materials formed conventionally (i.e. slip cast plaster or hand modelled ceramics). This is due to a lack of mechanical pressure and water which have the effect compacting the particles together.

These limitations represent some of the key challenges faced in the development of new materials for powder binder printing, as will be described in more detail in the chapters which follow.

Fused deposition modelling

Fused deposition modelling (FDM) was developed by Scott Crump in the 1980's and was commercialised by Stratasys, the company that he founded in 1988 [Palermo, E., 2013]. This technique utilises a thermoplastic filament which is fed through a heated nozzle and extruded onto a build platform. The object is 'laid down' as a semi liquefied bead along an extrusion path. The bead of material fuses to the previous layer and then hardens soon after extrusion as the material cools. There is no support material inherent to this technique, so if required support has to be generated and printed alongside the model. Support structures can be printed in the same material as the final object or in a soluble thermoplastic material; however, the latter requires the use of a secondary print head. Figure 33 shows a schematic of the FDM process; 1- Nozzle extruding the molten material, 2- Deposited material (modelled part), 3- Controlled, movable platform.

Figure 33: A schematic of the fused deposition modelling (FDM) process
[Image credit: © Zureks, Wikimedia commons (2016)]



FDM techniques typically work with thermoplastic materials such as nylon, *Acrylonitrile Butadiene Styrene* (ABS) and *Polylactic Acid* (PLA), however experimental composite materials have been developed which combine a thermoplastic binder material with a powdered filler such as wood, metal or ceramic [Warnier and Verbruggen, 2014, pg14].

FDM printers include the low-cost, consumer-style printers currently helping to bring 3D printing to a wider audience. Although some manufacturers still produce large, elaborate and expensive versions of FDM technologies (like Dimension 1200es from Stratasys), the lower cost printers are ideally suited to home, school and office use due to the fact that they can be operated relatively safely with the right precautions. Another benefit of these types of printers is that the mechanics can be simplified to relatively low-tech versions and if bought as a kit (for self-assembly) printers can be purchased for less than £200. These types of printers are popular among hackers and technology enthusiasts as they can be adapted to accommodate new materials. The resolution of the parts produced using most consumer style printers is relatively low compared to other 3D printing techniques. Additionally, the surface finish of FDM parts exhibit small striations on the surface as a result of the build process. FDM printing is therefore better suited for the production of parts where fine detail and very smooth surfaces are of lesser importance.

Ceramic paste extrusion

Ceramic paste extrusion, sometimes called Robocasting was developed at the Sandia laboratory, Albuquerque NM [Sandia National Laboratories, 1999]. Today the process typically utilises a commercially bought FDM printer that has been fitted with a modified extrusion head to enable the extrusion of ceramic pastes. The plasticity of the paste must be sufficient enough to enable it to flow through the nozzle orifice, yet once deposited it must be strong enough to support subsequent layers without collapsing/deforming. If the paste dries too slowly there will be a risk of the object slumping, yet if dried too rapidly there is also a risk of the object cracking, warping and deforming.

There are several different ways in which a FDM printer can be adapted to extrude pastes. One way involves the use of a stepper motor that pushes the plunger of a syringe containing the material. A drawback to the stepper motor technique is that the extruder mechanism is very bulky, with the total height of the extruder being at least twice that of the length of the syringe to enable the plunger to fully extend and retract. A syringe with a 60cc capacity and a fully extended extruder can reach up 40cm in length once nozzle and all other mechanisms are in place [Verbruggen, 2014, pg29].

The technique used for this research uses air pressure that is directly applied to the material in a syringe. The design for this technique is much lighter and less complex than the stepper motor technique. The syringe is sealed with a pressure cap which connects to an air compressor via a narrow tube. Air pressure is then controlled using a valve, which enables instant feedback for starting and stopping the extrusion. This is not a volumetric technique and the rate of extrusion is dependent on both the air pressure and the viscosity of the paste. If the paste viscosity changes, the air pressure needs to be altered to compensate for the change. This typically means that the process requires an operator to manually monitor and adjust the air pressure, so in effect it is not a fully automated system.

Capabilities and limitations of ceramic paste extrusion

Ceramic paste extrusion methods are capable of producing objects of good density, comparable to that of conventionally formed ceramics. This is due to physical and compositional similarities between a ceramic paste suitable for 3D extrusion and a good plastic clay body composition for hand forming. Both require the presence of china clay to facilitate forming and water to lubricate the clay particles. These two components have the combined effect of creating a fired body of good density due to sintering and fluxing action during firing.

For successful paste extrusion, sufficient water must be added to the ceramic components to enable the material to flow readily through the nozzle orifice, yet once deposited the material must be strong enough to hold its form without significant deformation. Some ceramic paste compositions extrude better than others. For example, a china clay body extrudes relatively well and has sufficient strength once deposited to retain its shape and support subsequent layers. A high silica composition such as faience tends to not extrude as well by comparison, requiring more water to enable the paste to flow through the nozzle orifice. Once deposited high silica compositions have very poor strength and tend to slump under their own weight. It is believed that particle shape plays an important role in determining how well a composition extrudes using this technique. China clay particles are plate-like in shape which slide readily over one another when a force is applied and retain their shape once the force is removed. By contrast, silica particles are needle-like in shape which lock together when a force is applied and fall away from one another once that force is removed. It is therefore important to balance the components in the paste to enable extrusion whilst at the same time maintaining the chemistry of the body to bring about desired aesthetic and physical properties.

Another benefit of 3D paste extrusion is that it is a low cost technique that is accessible to a wide community of people interested in exploring digital fabrication methods using affordable, desktop 3D printing technology. It is also an adaptable technology with a large open source community who freely share results and instructions on ways in which the technology may be customised for novel purposes (i.e. to facilitate a new material or modification to improve the performance of the 3D printer).

However, ceramic paste extrusion is a low resolution process. The resolution of objects produced using this technique is dictated by the size of the nozzle orifice. This in turn is dictated by the ability of a particular paste composition to flow through the nozzle orifice.

Most ceramic pastes and suspensions can be classified as non –Newtonian fluids. When extruding a non-Newtonian paste, the relationship between the amount of force applied and the amount of material extruded is non-linear. This means that more pressure is required to move less of the paste through the nozzle than would otherwise be needed to move a Newtonian fluid (such as water) through the same nozzle. Some ceramics pastes are also an example of a Bingham plastic, a material that behaves as a ridged body at low stresses, but flows as a viscous fluid at high stresses. The Bingham plastic tendencies of ceramic pastes require a certain amount of force to be applied before the material will flow.

The smaller the diameter of the nozzle orifice, the more pressure is required to move the material. Therefore, although a smaller diameter nozzle may bring about a higher resolution, it is more likely to result in failed fabrication attempts (e.g. due to the smaller nozzle clogging, or a leak in the system due to the very high pneumatic pressure that is required to extrude paste). It is therefore better to use a wider nozzle and accept or even embrace the resolution of this process.

Section 2: Contextual review: 3D printing material/process development for creative applications in art and design

The aim of this section is to contextualise the present research within the field of ceramic material and process development for 3D printing technologies and their creative applications within art and design.

This research covers a broad range of disciplines, therefore only the most relevant examples have been drawn upon for this review.

The contextual review will first discuss creative practitioners working in the field of material and process development for 3D printing technologies. Next several practical research projects that have focused on material development for the powder binder 3D printing process will be presented. This section will conclude with some of the most recent innovations and technological developments within the field of ceramic 3D printing.

Paste extrusion

Unfold is a Belgium based Design Studio who began work on ceramic paste extrusion in 2009. Conceptually, some of the work at Unfold has explored the connection between traditional wheel-thrown pottery and coiling techniques with the emergent ceramic paste extrusion technique. In an instillation piece entitled L'Artisan Electronique, designers at Unfold investigated the merging of craft, industry and digital making. The installation was set up as a miniature production line, featuring a simulated potter's wheel incorporating digital motion capture technology and software which was connected to an adapted FDM printer. Participants were invited to 'sculpt' a spinning lump of virtual material by passing their hands through a laser that detected the physical movement of the hand and communicated this to virtual space (see figure 34). Participants were then able to watch as their 3D model was printed in clay via paste extrusion (examples shown in figure 35).

Figure 34: Virtual potter's wheel, created using a 3D scanner and digital design software for l'Artisan Electronique by Unfold Studio.

[Image credit: © 2016 ThinkParametric, Inc]

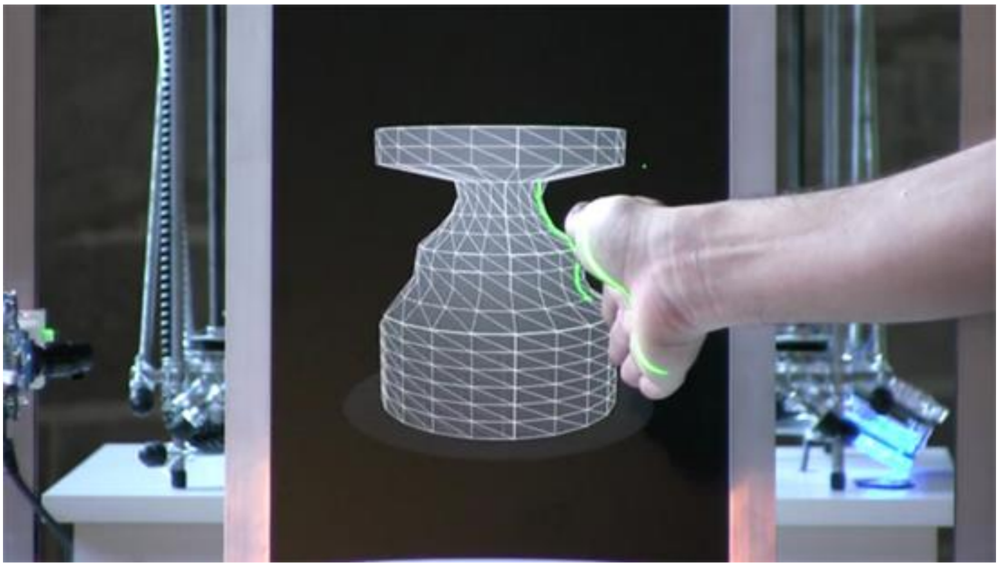


Figure 35: Extruded pots: l'Artisan Electronique by Unfold Studio

[Image credit: ©Unfold]

Johnathan Keep is a South African born artist who has also worked with ceramic paste extrusion. In 2011, Keep bought a RapMan FDM 3D printer, which came as a kit and required user assembly. With the help of the open-source community and some of the practitioners working at Unfold, Keep adapted his 3D printer so that it was capable of extruding ceramic pastes. Keep's work explores the mechanisms and evolution of natural forms through computer code and uses 3D printing as a tool to realise his computer generated forms [Hoskins, 2014, pg64]. Some examples of Keep's work are shown in figure 36.

Figure 36: Icebergs By Jonathan Keep. Objects formed through 3D paste extrusion [Image credit: Jonathan Keep, with permission from Keep. J, (2016)]

In 2012, Keep responded to a question posed at the beginning of the present research; *Can Egyptian paste techniques be used for 3D printing?* which was posted on the UWE website. Keep fabricated several objects in a faience paste using one of his adapted FDM printers. In a playful attempt to answer the research question, keep retorted that the paste 'prints fine' [Keep, 2012].

Figure 37: Objects formed through faience 3D paste extrusion (2012)
[Image credit: Jonathan Keep, with permission from Keep. J, (2016)]

These objects (shown in figure 37) produced by Keep demonstrate some of the limitations of using this approach to produce faience. These include a poorly glazed surface, presumably due to the faience paste components being compromised to enable extrusion (i.e. an increased china clay addition and reduced silica component) Additionally, unglazed areas such as the inside surface of the pot also result from a lack of airflow on these surfaces to draw the efflorescent salts to the surface. For a more complete glaze, geometries that are bulkier such as the cow example are more suitable. Another limiting factor of this material and process is that objects are limited to simple shapes due to the nature of the paste and its tenancy to collapse under its own weigh. Keep hand modelled the smaller, more delicate features such as the ears and horn features on the cow object and added them on after, showing that he too was aware of this limitation.

Powder binder printing

Art and design

Michael Eden is a ceramic artist who has used 3D printing and ceramic-like materials in his work. Before undertaking an MPhil at the Royal College of Art (RCA), Eden worked as a successful studio potter, selling functional and decorative ceramic wares to shops such as Habitat (UK) and Barneys (USA). With a growing interest in digital technologies, Eden began using CAD software as a design tool for exploring the form of an object, before making it using traditional pottery techniques (such as throwing and casting). For his final practical research project at the RCA, Eden produced his first digitally designed and fabricated piece. Eden redesigned an iconic symbol of the industrial revolution, a ceramic tureen designed by Josiah Wedgewood. Using CAD software (Rhino) Eden redesigned the tureen, giving it a delicately pierced surface inspired by bone structure and the natural objects used by Wedgewood and his contemporaries as a source of inspiration. The work was fabricated on a Z-Corp powder binder printer and was made in the commercially supplied plaster based material. Once built, the object was infiltrated to improve its strength and then coated in a composite ceramic material to alter the surface appearance. The ceramic coating was formulated to closely resemble the appearance of Wedgwood's black basalt ware (see figure 38).

Figure 38: Tureen by Michael Eden, 3D printed, ceramic coated Tureen (2008)
[Image credit: Michael Eden Tureen, with permission from Eden, M. (2015)]

Michael Eden uses the same 3D printing technique used in this research, however instead of fabricating his designs directly in ceramic materials; Eden applies a ceramic loaded resin to the 3D printed plaster model, giving the appearance of a glazed ceramics although it has not been glazed nor made permanent through the act of firing.

Industry and research

In 2010, Viridis3D LLC (Viridis) released Virishell, the first commercially available ceramic powder for 3D printing. Viridis was formed by Jim Bredt an original member of the MIT team and co-founder of Z-Corporation, and William Shambley, formally Director of Materials R&D at Z-Corporation. The ceramic body used in the Viridis process is an alumina and fused silica blend. Viridis went on to form a spin-out company called Figulo specialising in 3D printed ceramics for artists, designers, architects and businesses. The Figulo business was subsequently sold to 3D systems.

In 2009 Professor Mark Ganter from the University of Washington began experimenting with creating his own formulas for powder binder 3D printing. Frustrated with the high cost of 3D printing materials, Ganter began with replacing the commercially supplied plaster and starch based materials with standard pottery bodies, which he mixed with maltodextrin and sugar to enable binding. At the time, Ganter stated that the commercially supplied materials cost between $30 -$50 per pound (lb), whereas his formulations cost around $1 per pound to make. [Science Daily, 2009]. Ganter made the results of these experiments open-source on his website (Open 3DP 2015) in an attempt to democratise 3D printing and expand the range and accessibility of materials for powder binder printing. Other build materials that Ganter experimented with include glass, wood, paper and various ceramic bodies such as stoneware, earthenware and porcelain formulations. Also in 2009, ceramic artist and professor of Art at Bowling Green State University John Balistreri experimented with creating his own ceramic formulas for 3D printing. Unlike Ganter, Balistreri did not offer these formulations to the open source community, but holds two US patents related to ceramic 3D printing [Balistreri, J. 2015] now marketed as Tethon3D.

Centre for Fine Print Research (CFPR)

Researchers at CFPR have been working with in the field of ceramic 3D printing since 2007. The ceramic materials and processes developed at CFPR have been well received, resulting in collaborative industrial partnerships with a number of companies, such as Viridis in the USA and Johnson Matthey and Denby Potteries in the UK.

In 2012, CFPR researchers entered a licence agreement with Viridis granting them the exclusive right to market ViriClay, a 3D printable ceramic material developed by David Huson and Professor Steven Hoskins. This material is especially suited to the tableware industry as well as artists and craftspeople who wish to produce bespoke ceramic artefacts. At the start of 2015, Huson and Hoskins launched a spin-out company called Argillasys, who provide a quality bureau services for Ceramic Designers and existing ceramic companies. The company uses a patented ceramic body, to provide high value bespoke items for industry, designers, artists and crafts people. The materials and processes developed at UWE differ to other ceramic 3D printing techniques such as those used by Viridis, in that the UWE ceramic body more closely resembles a conventional tableware body, whereas the Viridis body is more like an industrial/metal casting ceramic material.

Recent innovations and technological developments in the field of ceramic 3D printing

Until relatively recently there had been very few significant advancements made within this field, however in 2016 a surge of innovations and technological developments were seen that have the potential to unlock the capabilities of ceramic 3D printing.

In early 2016, 'HLR Laboratories' (California) unveiled their new SLA (stereolithography) based process that is capable of producing fully dense, high strength ceramic parts that can withstand temperatures in excess of 1700°C. [Eckle et al. 2016]. SLA is a laser based 3D printing technology that utilises a photo-sensitive liquid resin. The laser beam scans the surface of the resin and selectively hardens the material, building the object layer by layer [Stereolithography, 2016]. HLR's version of this technology involves using a ceramic loaded resin and a post processing stage, where the polymer is removed through thermal de-binding, leaving behind the ceramic material. Applications of this technology include the production of jet engine components and microelectronics.

Israeli company 'XJet' revealed their pioneering NanoParticle Jetting technology in May 2016, which involves the deposition of ceramic Nano particles in a liquid suspension through inkjet technology to produce high strength, dense ceramic parts with a 2 micron layer thickness [Xjet, 2016]. This high resolution technology is particularly well suited to the dental and medical sectors.

The ceramic 3D printing company 'Admatec' exhibited its first ceramic 3D printer in September 2016. Using digital light processing technology (DLP) and a ceramic loaded resin. DLP is a form of stereolithography, however this process involves using a projector light rather than a laser to selectively cure the photo-sensitive resin. DLP can be quicker than SLA for the production of some parts as an entire layer is exposed to the light source all at once, as opposed to be drawn out with a laser [formlabs, 2016]. The material and process developed by Admatec is capable of producing dense ceramic parts that are particularly well suited for applications within medical, dental and jewelley sectors [TCT Magazine, 2016].

Also in 2016, HP launched its much anticipated Multijet fusion technology. This involves the deposition by inkjet of fusing and detailing agents onto powdered build material at a rate of 30 million drops per second. This process offers high precision and dimensional accuracy of parts and has huge potential in terms of the range of materials that could potentially be used and the degree of control over their properties [Griffiths, 2016].

Summary

This chapter has provided a general introduction to 3D printing technologies and a more detailed description of paste extrusion and powder binder printing techniques, as these are the processes used within this research. The capabilities and limitations of both of these techniques have been discussed in order to clarify the scope of this research.

In order to contextualise the present research within its field, a review of 3D printing material/process development for creative applications in art and design was conducted, as well as links to industrial applications and recent major developments within the field of ceramic 3D printing.