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Paste Deposition Modelling (PDM): A hybrid ALM/craft process

According to David Pye, handwork can be understood as two aspects of workmanship: workmanship of certainty and workmanship of risk. Craft, he argues, typically falls into workmanship of risk owing to the uncertainty of the outcome caused by lack of control over materials and processes.

The Aalto vase is an example of workmanship of risk; this design has evolved over several decades. It was originally made using wood moulds. This made each batch of vases unique due to the decay of the mould, which brought unique parametric changes to each vase.

This is in sharp contrast to Additive Layer Manufacturing (ALM) where the materials and the process are developed to the point of certainty. So, how in such a controlled process can we add elements of risk and uncertainty akin to craft? Would applying craft thinking give added value to the artefacts?

The development of an artefact through design software allows the designer-maker to attain a high degree of refinement. Cultivating a design can take several days. Has the relationship between maker and artefact shifted to a virtual plane?

> Contemporary craft is about making things. It is an intellectual and physical activity where the maker explores the infinite possibilities of materials and processes to produce unique objects. (Greenlees n.d.)

Makers in the realm of digital craft such as Drummond Masterton (2007) have explored the idea of disrupting CNC machine code to add aesthetic qualities, using machining marks as a primary design feature.

Materiality is essential to craft thinking – what materials are selected and how they are treated is of great relevance. In some ways current ALM processes have inadvertently, through delivering design freedom, limited this creative enquiry by reducing the palette of materials available to the designer-maker.

Paste Deposition Modelling aims to increase this palette and open ALM to experimentation. It relies on hacked together hardware and subverts software to explore syringe based 3D paste deposition. This approach enables designer-makers to 3D print with almost any material.

Silicones are easy to predict, and when considering the final form offer little uncertainty. However, the materiality of the build is far less predictable. It has surprising optical, structural and tactile qualities. Subtle differences in the internal structure can deliver great changes to the overall feel of the artefacts.

Craft materials like Precious Metal Clay (PMC) offer an opportunity to explore ALM in a context that is not normally associated with uncertainty. PMC is known for its unpredictability – variables in size and firing temperatures can influence the final outcome. PMC in clay form can be adapted for PDM using simple tools. Whilst a layered filament texture is evident from the process, it can be blended and made smooth, according to the designer's intention. It can also be exaggerated and exploited in a similar way to Masterton's work, leading to a more honest outcome of the process.

The process is much more open to 'happy accidents' where the material can be led to behave in unpredictable ways, leading to stochastic features not reflected in the virtual design stages.

PDM exists in three domains: digital, code craft, and traditional practice. This brings about a process that can be a hybrid in that it is ALM yet regains the nature of being 'touched by hand'.

Introduction

3D printing, Rapid Prototyping (RP) or Additive Layer Manufacturing (ALM) are synonymous terms for what has become a mainstream method for producing realistic models, or parts, from a 3D CAD file (*.stl). The steps are that the *.stl file is imported into the RP machine's software which slices the model into layers and processes the build orientation and any support required for the part to cope with overhangs. The model is then built by the machine 'bottom up' in successive additive layers.

There are many closed systems on the market and a limited spectrum of materials, most of which are suitable for prototyping purposes but often require a step-change with other processes to translate them into the correct material for purpose. In the jewellery sector an example would be the printing of wax masters for investment casting. Direct Metal Laser Sintering (DMLS) and other precursor metal ALM methods and systems have existed for many years but were still not developed for use in the field of jewellery by the time of this project.

In 2005, EOS demonstrated the possibility of sintering precious metals (Paynter 2005). Since then, EOS have collaborated with Cookson Gold to produce an operational machine.

Fused Deposition Modelling (FDM) is a process in which a spool of plastic filament is drawn into a heated nozzle which respectively plasticises the filament, enabling it to be deposited in layers according to the CAD data. A number of affordable entry-level FDM systems have emerged, e.g. 'RepRap', 'Bits From Bytes' and 'Makerbot'. These open up possibilities of ownership and, being less of a closed system, are easier to customise. FDM is perhaps the most similar to the build method used in PDM.

Coupled with the emergent open-design culture we see 'technophilic crafters "hack" machines, reverse engineer them and apply craft thinking on them to make them into open tools that can do new crafty things' (von Busch 2010: 119).

With current ALM systems the goal is to achieve near finished products so as to require little to no finishing by hand. The trend in ALM system development is towards higher resolutions to eliminate evidence of the process by reducing the layer height (stepping). In doing so, however, the opportunity to exploit the stepped quality of the process aesthetically is lost, without intentional programming. The exploitation of the stepping texture can be seen in the digital clock by Brian Podschies (Figure 1), where he intentionally exaggerated the stepping texture of the SLA process across the top of the piece to use it as an aesthetic feature. He then used this print as a form to cast in polyurethane which he then electroformed in silver.

Figure 1. Electroformed silver clock by Brian Podschies © Brian Podschies, image used with permission.

The approach of leaving the evidence of the process leads to a more honest outcome. This is similar to the digital deconstruction method created by Drummond Masterton (2007). However, instead of using additive manufacturing he uses subtractive methods, cutting into blocks of material using a CNC mill (Figure 2). CNC machining leaves cutting marks and patterns on the surface of the material. In the industry, these are usually polished away. However, Masterton focuses on using these as the primary aesthetic feature of his work. He interferes and manipulates the machine code to create patterns and cutting marks that are distinctive to his visual vocabulary, 'taking advantage of the unique circumstances that the tools can provide, and moving beyond using the tools to simply aid in the speed or ease of production' (Campbell 2007 :61). In doing so he takes greater ownership of the final artefact. By modifying the machine code, he overrides the decisions the machine has made on how to make the intended part and manipulates them to achieve his desired outcome.

Figure 2. 'KOM' by Drummond Masterton (2012) © Drummond Masterton, image used with permission.

The phrase 'workmanship of risk' means that at any moment, whether through inattention, or inexperience, or accident, the workman is liable to ruin the job. It is in opposition to the 'workmanship of certainty', in which the quality of the result is predetermined and beyond the control of the operative. (Kelsey 1995: 9)

David Pye argues that craft typically falls into workmanship of risk owing to the uncertainty of the outcome caused by lack of control over materials and processes. However, this also opens the field to experimentation and creative enquiry as the range of tools and techniques that can be applied to workmanship of risk are larger than those that can be applied to workmanship of certainty.

The Aalto vase is an example of workmanship of risk. The vase was originally made by blowing glass into a wood mould – each mould was hand crafted and used several times. Over time the glass would burn the mould, producing a parametric change, meaning that even vases made from the same mould would not be identical. The manufacturing process has changed in recent years to meet demand and the workmanship has shifted to certainty by using steel moulds where each batch is identical.

ALM can be considered to be workmanship of certainty as the outcome is for the greater part beyond the control of the maker as long as the parameters and machine set-up are correct. In such a controlled environment makers are able to dedicate most of their time to the development of form through CAD software to exploit the properties of the system and the material to the very limit, producing results that can surpass the expectations of the material.

This can be seen in the N12 bikini designed by Mary Huang and Jenna Fizel (Figure 3). Here the packing and linking of the components that make up the bikini have been calculated using an algorithm to produce the desired shape and mechanical properties in Nylon 12 using selective laser sintering. This example shows that there has been a shift in the materiality of making towards the digital domain given the limited spectrum of materials available to the process. Makers have to find new ways to exploit the material and use the freedoms provided by the manufacturing technique to produce the desired functions. However, they are still limited by what is physically possible with the given material.

Figure 3. 'N12' SLS printed bikini by Mary Huang and Jenna Fizel. Photographer: Esteban Schunemann © Esteban Schunemann.

Materiality is essential to craft thinking – what materials are selected and how they are treated is of great relevance. While many practitioners have attempted to adapt to the limited range of materials available for experimentation by working with what is available, the fact still remains that closed ALM systems are designed to be user friendly and have limitations built into the software to ensure optimal conditions. This is reflected in the materials used by the process as they are both finely tuned to the point of certainty.

The research draws upon the development of open systems. It uses hacked together hardware and subverts software to explore syringe based Paste Deposition Modelling. It aims to extend the materials available for ALM. It does this by using a CNC machine as the platform for 3D deposition of materials (Figure 4). This approach overrides any need for firmware in the system as it is driven in real time from a computer. The pneumatic syringe based deposition heads allow for almost any material to be deposited, as long as it is in paste form.

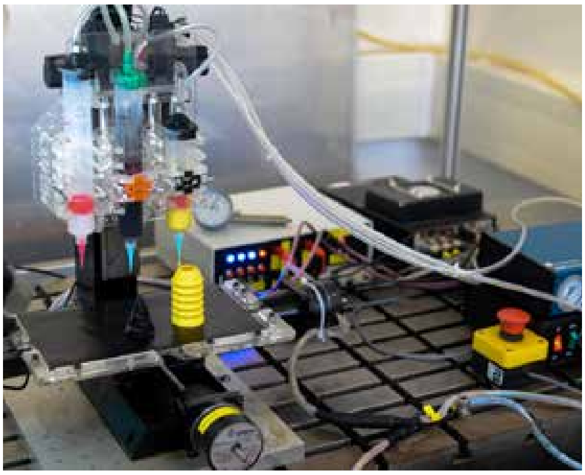

Figure 4. Experimental set-up. Esteban Schunemann (2012) © Esteban Schunemann.

> Craft relies on tacit knowledge. Tacit knowledge is acquired through experience and it is the knowledge that enables you to do things as distinct from talking or writing about them. (Dormer 1997: 147)

The nature of the research in this project is practice based. It delves into ideas and applications with different materials in order to gain experience and understanding of the process. Areas of investigation have included medical devices, embedded electronics, product design and jewellery. This article covers the deposition of silicone and metal with some examples and applications.

Code generation

File preparation for ALM generally makes use of slicing software. This generates instructions for each layer of the object including infill patterns and surface perimeters.

This automated process, however, does not allow the designer freedom to generate unique patterns pertaining to the designer's visual identity. To overcome this limitation, the layers of the object are designed individually in 2D within CorelDraw and exported to G-code, where the sequence of layers can be repeated in code as required; this method is more suited for straight walled builds. Alternatively, the layers generated in CorelDraw can be imported into 3D Studio Max and edited there to create more complex surfaces such as twists and overhangs (Figure 5). This approach allows for greater control over the geometry and the resulting visual and tactile qualities of the artefact. If need be, the system can also use G-code generated by a standard slicer such as Slic3r.

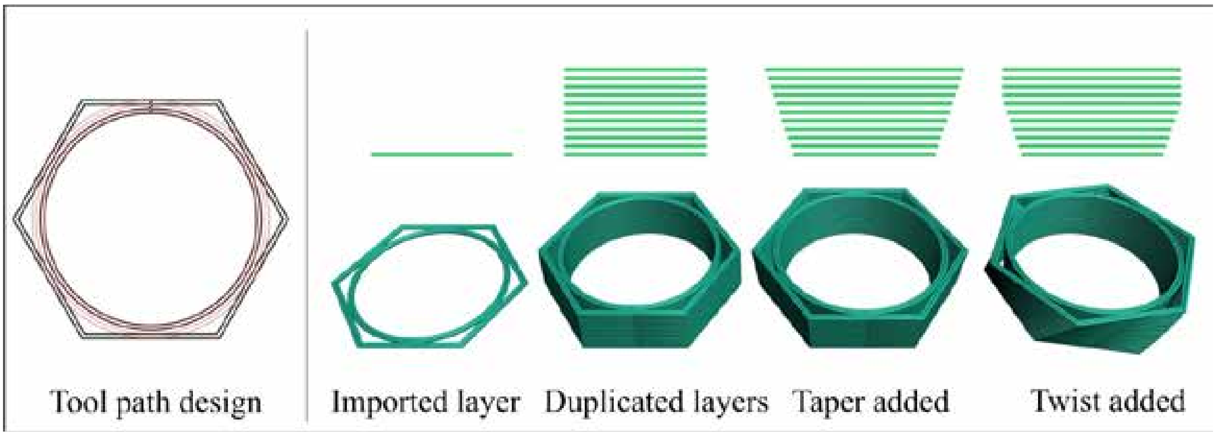

Figure 5. Tool path development diagram. © Esteban Schunemann.

Materials, preparation and syringe loading

Metal clays

Metal clays consist of metal particles suspended in an organic binder which burns away upon firing; the metal particles also sinter and produce a near fully dense metal part.

Precious Metal Clay (PMC) is a silver clay that emerged in the 1990s manufactured by Mitsubishi Materials; other brands such as 'Art Clay' also exist and pre-formulated metal clays are also available in bronze and copper. Conventional techniques used with metal clays are similar to those used in ceramics and pertain to craft, although the final object is commonly jewellery.

One of the fundamental issues of metal clays is that, despite the manufacturer's guidelines, it is difficult to predict the shrinkage from the particles sintering. This is a relative black art, dependent on the geometry and scale of the item. It is also dependent on the specific clay formulation in terms of particle size, homogeneity, particle shape, and proportion of metal particles to binder. Some characterisation of the sintering process, relative shrinkage and the resulting material properties of the various formulations of PMC has been undertaken by (McCreight 2010).

For the tests in metal detailed in this article, two types of clays were used: BronzClay and PMC Pro (90% silver). PMC Pro was chosen over 'PMC3' (pure silver) as it is a stronger material (Cool Tools). In a 2010 study, Sanderson demonstrated the relative strength of 'PMC Pro' by practically working the metal and sizing rings (Sanderson 2010: 7).

Material preparation

Metal clay as sold is too vicious for deposition, so to prepare it fresh clay is spread on a smooth surface (e.g. glass) with spatulas. Distilled water is gradually added with an atomiser. Olive oil is also added to help condition and lubricate the clay. This procedure is 'hands on' and the proportions vary depending on the age of the clay and how long it is mixed for, but roughly the proportions are 4–8 grams of water and 0.1–0.5 grams of olive oil for every 50 grams of clay. Typically, PMC Pro required more water to prepare than BronzClay to reach a suitable viscosity. The result is a paste with a viscosity comparable to peanut butter. Silicone required no preparation as standard off the shelf acetoxy silicone was used.

Syringe loading

Mixing with spatulas reduces the amount of air that gets inside the clay. When loading the syringe, however, some air is introduced; large air bubbles can lead to deposition interruptions which can ruin a build.

To reduce the likelihood of large air bubbles, the paste is first loaded into a syringe that is used to load the depositing syringe from the front. This double loading method helps diffuse the large air bubbles in the clay. The silicone was also loaded with a similar front loading method, but it was done directly from the silicone cartridge.

Silicone deposition

Elastomers in ALM are not common. Systems like Objet feature rubber-like materials but they are not durable and only suitable for prototypes. The rubber-like material has the advantage that it can be combined with rigid variants of the material to simulate different levels of shore A values (Stratasis A 2013). However, there is no chemical resistance data on these materials and, furthermore, the maximum elongation achievable by the rubber-like material is 170% (Stratasis B 2013: 3). These limitations can be overcome by using silicone in PDM. The material is readily available and can be matched to the application.

Deposition perimeters and stability

For 3D deposition in silicone to be possible, the material must be self supporting. Otherwise the structure would collapse in the first few layers or each layer would require curing before consecutive layers could be added, insofar as all the silicones tested have demonstrated excellent self support properties. Figure 6 shows a 100 mm tube built in clear silicone with no infill or support structures; this build took fifteen minutes to complete. The curing time of this silicone is 4 mm per day but it can be handled within one hour.

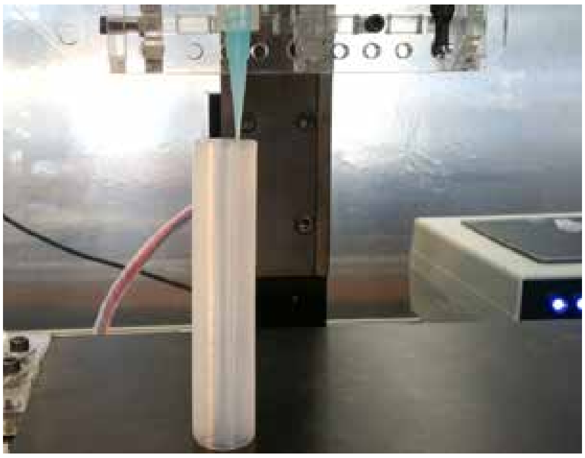

Figure 6. Deposition of silicone tube, 100mm tall. Esteban Schunemann (2012) © Esteban Schunemann.

While the silicone might be self supporting it is important to consider the structural integrity of what is being built. The 100 mm tube was made with two perimeters per layer; these make up the wall of the build. Previous build attempts failed when only one perimeter was used, this is because filaments are cylindrical and therefore inherently unstable. Figure 7 illustrates the issue. The draft angle of the structure is also of importance. When the build reaches 45° one of the filaments with be deposited in mid air unless there is an infill or support structure underneath to support the filament.

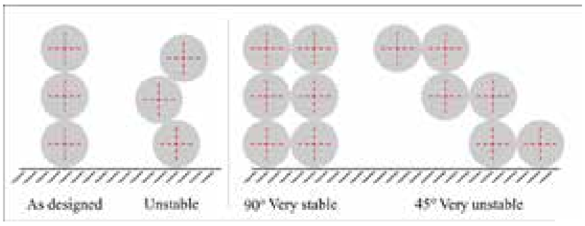

Figure 7. Perimeter stacking diagram. © Esteban Schunemann.

Mould deposition

The elasticity of silicone makes it ideal for moulding applications. The manufacturer of the silicone used claims up to 800 per cent elongation at breaking point with a working temperature range of -40°C to +180°C (Mapei 2011).

Several hollow builds were made, primarily to test the limits of deposition but also to test if they were water tight and therefore suitable for moulding. Figure 8 shows one of the moulds (yellow) taking just under four hours to make with a 0.4 mm nozzle and three perimeters. The second mould, nicknamed 'the seashell' (red), was made using a 0.8 mm nozzle to exaggerate the filament texture and save time. This build was completed in one hour with three perimeters.

Both moulds were found to be water tight and were tested for their suitability as moulds by casting resin and gelatine; both successfully de-moulded. As a final test the yellow mould,, being the thinnest and most flexible, was also tested with cake mix and baked in an oven; while the silicone is not food safe it served well as proof of concept. The silicone was able to withstand the temperature and remain flexible after baking; it showed no signs of discoloration or burning.

Figure 8. Silicone moulds. Esteban Schunemann (2012) © Esteban Schunemann.

Silicone textiles

ALM is suitable for making complex shapes and products that would perhaps be too difficult or impossible to make by traditional methods. In this case the properties of the silicone were exploited to make textiles (Figure 9). The build is quite simple – it consists of two layers of silicone in a log-pile configuration; a 0.6 mm nozzle was used to extrude the filaments. Initially it was thought that the filaments were too thin and the textile would be too delicate to handle but, surprisingly, it is quite strong and able to withstand being stretched.

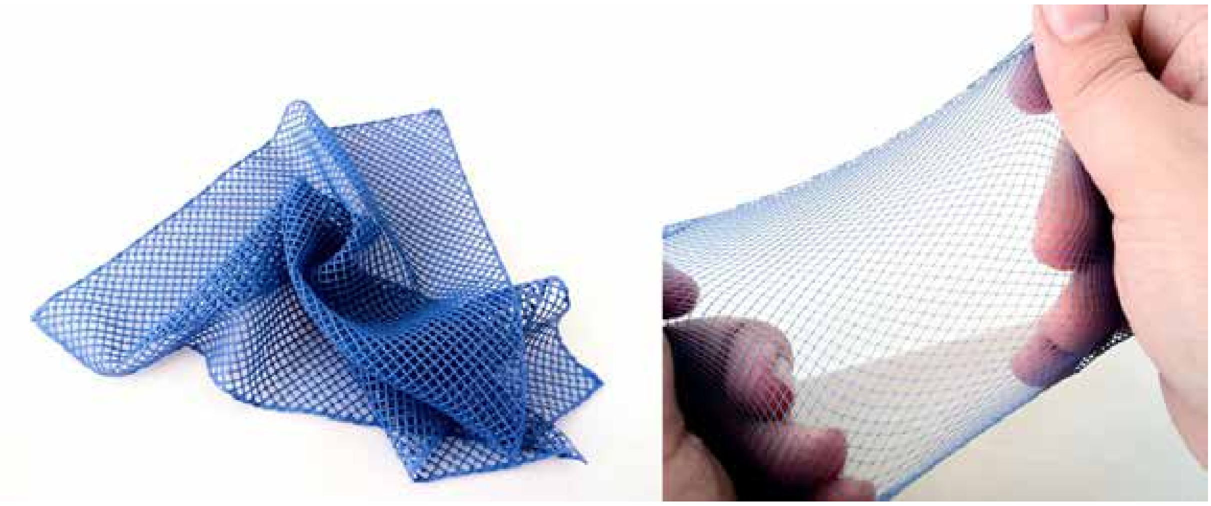

Figure 9. Silicone textile. Esteban Schunemann (2011) © Esteban Schunemann.

Silicone watch

The work on the silicone watch constitutes a milestone in terms of the development of the machine and the experience gained in depositing with silicone. A new version of the deposition head was developed during the tests leading up to this build to support up to three deposition heads with an automatic tool changer. The watch is a multi material build featuring both clear and opaque silicones and an embedded digital watch movement which was added during the build to encapsulate it inside. The image on the right in Figure 10 shows the moment the movement was installed. The infill was designed to maintain an even cell distribution along the whole band to make it soft and comfortable to wear. The whole build took four hours to complete with a 0.8 mm nozzle.

Figure 10. Silicone watch finished (left), movement installed (right). Esteban Schunemann (2012) © Esteban Schunemann.

Silicone process discussion

The work in silicones in terms of the form poses little uncertainty. As long as the deposition set-up is correct, however, what is uncertain from the virtual model is the materiality of the build and how the artefacts feel and behave when handled – it is a tactile experience.

The moulds functioned well without any tearing. Few materials bind to cured silicone so this makes it ideal for mould making. The shape of the seashell would be a very complex form to machine in order to make a mould, so even with the curing time of the silicone it is still a very fast method for producing bespoke moulds. This could have potential applications in the cake decoration industry as complex moulds can be manufactured with a short lead time.

The watch demonstrates the importance of control over the deposition process. The model could not have been made using an automated slicer; it is impossible for the creator of the software to anticipate all possible applications and intentions the maker might have and provide optimised solutions for each. The infill (blue in the pictures) used in the band of the watch went through several iterations until it reached the softness and flexibility that was desired. The window of the watch made in clear silicone makes a lenticular effect over the display; as the light is diffused through, it creates an intriguing effect where the light becomes interlaced with the filament pattern.

The versatility of PDM in silicones is manifested in the silicone textiles. The movement of the textile is organic in nature, flowing and yielding. Just the theme of making textiles with silicones can render an infinite number of possible permutations and patterns to explore, each with different applications. This is the aim of PDM – to open ALM to a tree of exploration with infinite branches.

Deposition of metal clays

Key research questions concern whether metal clays can be adapted for 3D deposition. In the first instance this means diluting them to a consistency that will pass through a tapered syringe nozzle, determining the deposition parameters, and finally seeing whether the reformulated material will sinter fully. From initial results, a range of 3D geometries that show the limits of deposition can be developed. Finally to show how such materials, within the constraints found, may be used for jewellery, a range is developed that suitably aligns the aesthetics of PDM and the possibility of self-originated infill structures with the intentions of the designer. This is subsumed within the creation of rings as they demonstrate the ability to create a product to a set size, taking into account material shrinkage during firing. It is considered that the internal structure of the part achieved by infills may also have an effect on the overall shrinkage.

Preliminary tests

To build the knowledge required for deposition, basic test geometries were deposited in BronzClay; these included simple log pile structures and cones featuring draft angles from 30° up to 45° at 5° increments. The cones were made to determine the maximum draft angle the clay could be deposited at unsupported. The firing schedule was based on the manufacturer recommendations (RioGrande 2011: 9). The 30° and 35° cones built well. The first few layers had the tendency to slump due to the weight of the material, but as the diameter of the layer decreased the structure became more stable. This scenario, rather than producing a regular cone, results in something of a 'witch's hat'. At 40° the inner filament struggled and became detached from the layers underneath at several points (Figure 11). The build completed but the surface quality was less than ideal.

Figure 11. 40° draft angle cone, being deposited (left), fired (right), BronzClay. Esteban Schunemann (2012) © Esteban Schunemann.

At 45° the deposition failed (Figure 12). The steep angle meant that the innermost filaments were deposited in mid air, causing the layers to collapse. This meant that further layers were now being deposited too high, causing the filament to coil and move randomly as the build progressed. The unpredictability of the filament placement under these conditions can become something that is desirable.

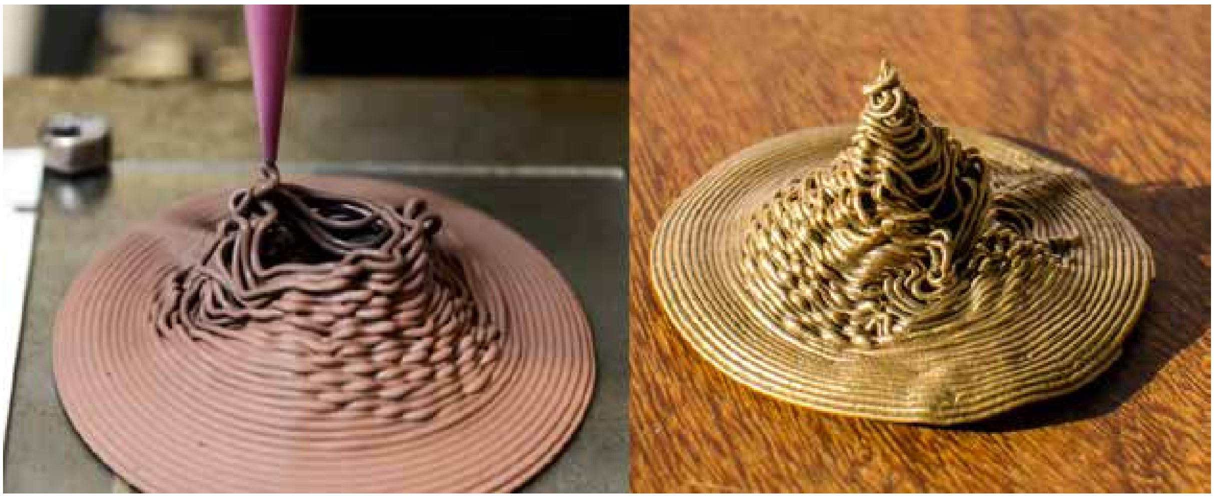

Figure 12. 45° draft angle cone, being deposited (left), fired (right), BronzClay. Esteban Schunemann (2012) © Esteban Schunemann.

The cones were used to underpin the development of the process towards producing sophisticated hollow builds. Another build was made in both BronzClay and PMC Pro using the geometry made for the seashell silicone mould (Figure 13).

The seashell was sliced with the same parameters used on the cones. While depositing in BronzClay there was an issue with the air supply which caused the pressure to constantly rise and fall. The effect was that the filament became finer as pressure fell, and as the pressure rose it became thicker. Consequently it became necessary to manually adjust the feed-rate in 'Mach3'on the fly. While the print was successfully completed, the surface had a wavy quality that was not part of the design. It is worth considering, however, that this brings forth ideas as to how the effects of varying the flow-rate could be used for aesthetic purposes.

Figure 13. Seashell build in PMC Pro (left), BronzClay (middle) and CAD model (right). Esteban Schunemann (2012) © Esteban Schunemann.

The seashell test showed that PMC Pro has a higher tendency to slump than ‘BronzClay’; this could be partially due to it having a higher water content. This was observed early in the build, and to alleviate the slumping air from the supply was directed at the build platform. This helped the build dry quicker as it progressed and lessened the impact of the slumping.

Tessellated rings

Several rings were designed where the infill was the primary feature. These rings were used to observe how much shrinkage occurred in the rings. They were made in both PMC Pro and BronzClay. The firing schedule for PMC Pro was based on work by Sanderson (2010), where she attempted to characterise the shrinking of PMC in the context of rings and how the firing stage influenced the final outcome.

The BronzClay rings warped during firing – the geometry became elliptical and was no longer flat. The rings were strong enough, however, to be hammered flat. The elliptical shape was then rounded on a ring mandrel; the rings were not stretched. In contrast PMC Pro rings showed little warping and only required a few light taps with a mallet to make them fully flat and round. The shrinkage was consistent when comparing the rings made with both materials; which was 14.5 ring sizes. Figure 14 shows a comparison between a fired and unfired ring.

Figure 14. Tessellated ring shrinkage comparison in BronzClay. Esteban Schunemann (2012) © Esteban Schunemann.

Hex rings

These rings featured a lighter geometry with no infill to ascertain if the thick infill of the previous test had any influence on the shrinkage. The rings were made in two batches to observe how the rings shrank and then make dimensional corrections to the design to target a specific size in the second batch. The first batch of rings shrank less than the tessellated rings, which suggests that the infill did influence the shrinkage. The ring with the dimensional corrections shrank marginally less than the first batch; yet, due to the uncertainty of the shrinkage, the ring was designed to be smaller than required so that it could be sized up if need be; it is easier to go up one or two ring sizes than going down. Nevertheless, the size was close enough to correct on a ring sizing mandrel. The overall shrinkage of these rings was between nine to ten ring sizes. One of the rings from the first batch was burnished with water and sanded smooth before firing to test how the deposited clay would react to working using traditional techniques. The rings were finished with a patina to emphasise the filament texture.

Figure 15. Hex rings in PMC Pro. Esteban Schunemann (2012) © Esteban Schunemann.

Large rings

These rings were made as an exploration using the experience gained from the previous work. They were burnished and made smooth on the outside surfaces but left untouched inside to contrast the filament texture against the smooth surface (Figure 16).

The cityscape ring (BronzClay) was heavily worked in its greenware state by cutting, burnishing and sanding to observe how far the deposited clay could be pushed. The shrinkage of this ring was 13.5 ring sizes, which was greater than the hex rings but smaller than the tessellated rings.

The suspension (PMC Pro) ring was burnished on the outside and light sanded. This ring shrank less than expected at 8 ring sizes.

Figure 16. Suspension ring in PMC Pro (left) and cityscape ring in BronzClay (right). Esteban Schunemann (2012) © Esteban Schunemann.

Metal process discussion

The creation of texture goes beyond the digital domain. The material can be led to behave in a stochastic fashion; by depositing at less than optimal parameters filament placement can be unpredictable, breaking the symmetry of the layered texture and producing something unique. This was observed during the cone draft angle tests where the print failed at 45° (Figure 12). This shows the process is open to 'happy accidents' where key aesthetic features are not reflected in the virtual design stages.

It has been shown that metal clays can be adapted for PDM. They can be prepared with large tolerances using simple tools and dispensed through a syringe nozzle. Firing schedules were determined and it was found that 'BronzClay' and 'PMC Pro' sintered fully and could withstand basic wroughting. Seashell geometries (Figure 13) demonstrated that PDM can produce sophisticated, tapered and twisted parts without support material, which bodes well for creating 3D hollow parts. Benchmarking the dimensional stability of metal PDM by ring size shrinkage was attempted. This was combined with developing a body of work to demonstrate some anticipated benefits of coupling the PDM characteristics with self originated infill strategies. Where consistent batches were fired as built (i.e. not worked by hand), there was good consistency within the batch but not between different designs.

This is likely to be dependent on the design features of: external and internal perimeter geometries, infill patterns, wall thicknesses and build height. PDM is in its infancy. For it to be dimensionally reliable, a more formalised experimental approach would be required. This would encompass process development rather than a crafts research based context. An exploration of metal PDM for craft outcomes that are not dimensionally constrained would appear an appropriate way forward.

Further to the investigation with the rings, another piece was made. A pendant was designed as a visual expression of the tessellation patterns PDM is capable of when not dimensionally constrained as per previous tests (Figure 17).

Figure 17. Pendant in PMC Pro. Esteban Schunemann (2013) © Esteban Schunemann.

With PDM for metal clays there isn't a step-change, and only the material required in the part is prepared, rather than a bed of powder. This, combined with the desktop prototyping merits, could be an open-source, low-cost and versatile process for cold forming metals, making it ideal for one-offs or small batch production requiring little set-up cost. This presents a viable route for designer-makers wishing to work with ALM in precious metals.

Conclusion

What has been presented here is a process which allows makers to take ownership of the artefacts made with the process by encouraging creative enquiry and allowing the maker to take control of ALM and make active decisions that are pertinent to the craft process and the maker's visual identity.

Generating PDM program files is a multi-step process that could be deemed complex and off-putting for many, but not all. It is an approach in the open-source domain common to many types of research. Masterton (2007: 20) created a process for intervening in the automatic generation of cutting tool paths for metal decoration using Corel Draw. PDM similarly offers opportunities for design by control of the tool paths and infill patterns. Ideally a platform based system to develop geometries and tool paths is needed. As such approaches become mainstream, they should eventually grab the attention of software developers.

The layered PDM creates a texture which can be exploited within the product's visual identity. PDM can deposit using a number of different sized nozzles. The capability to deposit even larger filament diameters allows for further exaggeration of the texture. The ability to quickly change filament diameter makes this a re-configurable arrangement that is less directed by the constraints of the 0.1 to 0.4 mm filament diameters typical of FDM. Whilst a layered texture is evident it can also be selectively blended and made smooth, according to the designer's intention. This brings about a process that can be a hybrid in that it is ALM yet regains the nature of being *touched by hand*. This approach presents a change in the nature of practice, one in which coding skill needs to become part of the designer-maker's toolkit to take full advantage of the freedoms offered by the process.

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