https://doi.org/10.7577/formakademisk. 5423

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Twisting Clay

Creative Research to Explore the Complex Rheology in Ceramic Extrusion

ABSTRACT
This paper details practice-based research exploring new creative possibilities involving the ceramic extrusion process. The paper begins by providing a short overview of the extrusion technique, its characteristics and some contextual coverage of the process. The paper then describes how both tacit knowledge and theoretical material understanding have been used to overcome technical challenges through iterative research cycles and how, ultimately, the aesthetic qualities of the extrusion process have been used to develop a body of creative work. A key theme of the research is how digital fabrication technologies can be used in toolmaking scenarios to deliver innovation with a process that has long been used in craft ceramics but has remained somewhat underutilised.

Keywords:
Toolmaking, Ceramic Extrusion, Rheology, 3D Printing, Craft Innovation.

BRIEF HISTORY, CONTEXT AND BASIC PRINCIPLES OF CLAY EXTRUSION

The basic principle of extrusion is to create physical shapes by forcing a pliable medium through a profile, commonly known as a *die*. The use of extrusion to form clay into products can be traced back to the early seventeenth century, with the first known example being an extruder developed for the production of bricks. However, it was not until the mid-nineteenth century that clay extrusion began to be used more widely for architectural ceramic components (Händle, 2007, pp. 100–108). During the twentieth century, extrusion became increasingly common as a highly efficient method for the production of ceramic bricks, water pipes and tiles. While a number of minor innovations have gradually been introduced, the core approaches with the process have remined largely unchanged, both within industrial and craft sector use. In terms of the basic propulsion two core approaches are used; *piston* or *auger*. The auger approach is based on an Archimedean screw principle to propel the clay through the extrusion die. Although it requires significantly higher levels of engineering to manufacture extrusion machinery, this approach has the capacity to provide a continuous flow of output and is therefore overwhelmingly the preferred option in industrial production. The piston principle is based on the use of a basic ram to force clay through the extrusion die and is a very simple mechanical system to construct; consequently, it is the most commonly used method in craft practice.

Examples of ceramic extrusion use in craft and designer-maker practice

Clay extrusion has long been employed in the craft pottery sector, although primarily as a *supporting* technique to produce handles and other minor elements, with small, hand-operated piston extruders utilised for this purpose. Despite the widespread use of such extruders, the process has been largely overlooked as a primary production tool, with only one article, by Pancioli (2000), dedicated to the subject. However, there are still a few notable examples of ceramic practitioners that have explored the technique with some more innovative approaches, including Floris Wubben (www.floriswubben.com), Max Cheprack (Hîrdo, 2012) and Anton Alvarez (www.antonalvarez.com). Granby Workshop has also utilised the extrusion process for an architectural installation in collaboration with Assemble Architects (https://assemblestudio.co.uk/projects/a-factory-as-it-might-be). Studio Apparatu has provided examples of how the extrusion process can be effectively used beyond the convectional applications with inspirational furniture and interior designs produced by the method (www.apparatu.com).

FIGURE 1. Examples of the use of extrusion in craft and design practice. (Far left) Floris Wubben's extruded *Throne* (2022) (photo: F. Wubben, 2022, permitted reproduction). (Centre left) Small hand-operated extruder commonly used in craft ceramics (photo: T. Jorgensen, 2018). (Centre right) Metal extrusion dies by Studio Apparatu used for Xavier Mañosa's (2018) designs for ceramic shelf brackets (far right). (Photos: Jara Varela 2018, permitted reproduction)

Characteristics of ceramic extrusion

The principle of extrusion is highly dependent on clay's characteristic of *plasticity*. This particular property can best be defined as a medium's capacity to be moulded or altered without fracturing. Clay is weathered rock, and as a naturally occurring soil material, it is hugely variable, with the levels of plasticity equally inconsistent. While the mineral constituency of a particular clay body affects its plasticity, the key aspect that provides clay with plasticity is the amount of water with which it is mixed, as outlined by Atterberg (1911). Thus, clay paste cannot be considered as a single homogenous medium but one that is semi-solid or that has both a solid and a liquid phase (Benbow & Bridgwater, 1993, pp. 1–6). These highly variable parameters mean that the task of predicting clay's behaviour in an extrusion situation is very challenging. An initial perception of plastic clay could be that the material behaves as a solid mass, and in some situations, that is the case. If a ball of clay is picked up and handled, it would generally follow the laws of physics that are applied to the behaviour of a solid mass. However, when the clay is manipulated (pressurised) in an extrusion situation, it behaves more like a liquid than a solid, and thus is in line with *non-Newtonian* behaviour (Chhabra, 2010). Rheology is the branch of physics that focuses on understanding the deformation and flow of matter under force, including the behaviour of plastic bodies, such as clay, in non-Newtonian situations. Some work has been done to develop theoretical models that can to some extent predict the behaviour of clay extrusion. John Benbow was the first to present an equation to model this behaviour (Benbow et al., 1989, 1991). Further work on this theoretical modelling was undertaken in collaboration with John Bridgwater with an example of the equation illustrated in Figure 2. While the Benbow–Bridgewater equation has undergone empirical testing by other scholars and been found to have reasonably good accuracy (Guilherme et al., 2009; Vitorino et al., 2014), this equation is only focused on predicting the *forces* needed to extrude clay through a particular extrusion die geometry. It does not estimate the behaviour of the clay exiting the die or the unexpected effects of the extruded clay parts, such as curving or having surface defects.

$$P = 2(\sigma_0 + \alpha V^m) \ln\left(\frac{D_0}{D}\right) + (\tau_0 + \beta V^n)\frac{4L}{D}.$$

FIGURE 2. A version of the Benbow–Bridgewater clay paste extrusion equation, in this case calculating the pressure in a die with a circular cross-section and a square entry feed.

Apart from ceramics, extrusion is used with multiple other mediums, including metals and polymers. Simulation software, such as Qform3d and Ansys, have been developed to assist in die design for these media; however, due the additional material complexities of clay, such software does not seem to have been developed for ceramic production. Contextual research on the architectural ceramics sector, where the industrial use of the extrusion process is most prevalent, has not found any examples of companies using simulation to design extrusion dies or predict production issues through this approach. The key requirement for the industrial use of the extrusion process is to ensure the clay flows at an equal rate through the die profile to create straight and consistent extruded parts. If some of the many variables associated with the rheology of extruding plastic clay affect this situation, the clay may flow faster through some parts of the die, which can cause the extruded clay to curve or buckle or cracks to develop during the subsequent drying process. To combat such problems, highly skilled operators adjust the die with inserts that either restrict or encourage the flow of clay in particular sections of the extrusion die, a practice that is known as *balancing* the die.

FIGURE 3. (Left) Industrial ceramic extrusion at the Ibstock brick-making factory, UK. (Right) The large industrial die with an insert added (in lighter colour) to adjust the flow of the clay in the die. (Photos: T. Jorgensen, 2023 (left) and 2019 (right))

PRACTICE-BASED RESEARCH – RESEARCH QUESTION AND METHODOLOGY

The creative investigation described in this paper is *one* part of a wider, ongoing research project that seeks to investigate the use of ceramic extrusion in novel applications in sectors including aerospace and sustainable construction. One of the aims of this wider inquiry is to use craft research approaches to deliver new knowledge and innovation in sectors not typically associated with craft practice. The investigation detailed in this paper forms part of this wider research but is focused on exploring new *creative* possibilities with the extrusion method through the use of digital fabrication in toolmaking scenarios. The research seeks to cross-fertilise knowledge and experiences from other knowledge domains, including contextual research on industrial usage and theoretical knowledge of extrusion rheology. Thus, the research question for this specific enquiry can be articulated as follows:

- How can digital fabrication and knowledge of the complex rheology of the extrusion process be explored through creative investigations to develop a series of twisting ceramic vases?

The practical investigations in this study were carried out with an empirical research approach broadly structured with an action research methodology (Cohen et al., 2007, pp. 297–313; Lewin, 1946; McNiff, 2002) with iterative cycles of investigations within the lead author's own creative practice. Within this cyclical structure, further notions of *tacit* (Polanyi, 1966) and *material thinking* (Carter, 2004; Tonkinwise, 2008) also informed the inquiry. In particular, the researchers' experiences as art and craft practitioners with years of experience with the clay medium underpinned the inquiry through a kind of 'knowing in action' (Schön, 1992). As the core of the enquiry is focused on a process (extrusion) and medium (ceramics) this research could best be described as a *process-oriented* exploration however with a creative aim still guiding these explorations.

Toolmaking

It can reasonably be argued that the most central component of ceramic extrusion is the actual extrusion die, and while this paper primarily focuses on the development and use of this part, the researchers feel that is important to highlight the central role that the notion of *toolmaking* on a wider level played in this inquiry. In this regard, it is relevant to note that the extrusion machine used in this research was designed and constructed by the researchers using basic, off-the-self components in combination with some bespoke stainless-steel parts fabricated by CNC laser cutting. The core concept for the extrusion machines is based on a simple piston approach, albeit with an industrially rated hydraulic system to operate the piston (Figure 4). The hydraulic system provided the extruder machine with very high levels of power, with up to 230 bar available within the system to force clay through the extrusion dies.

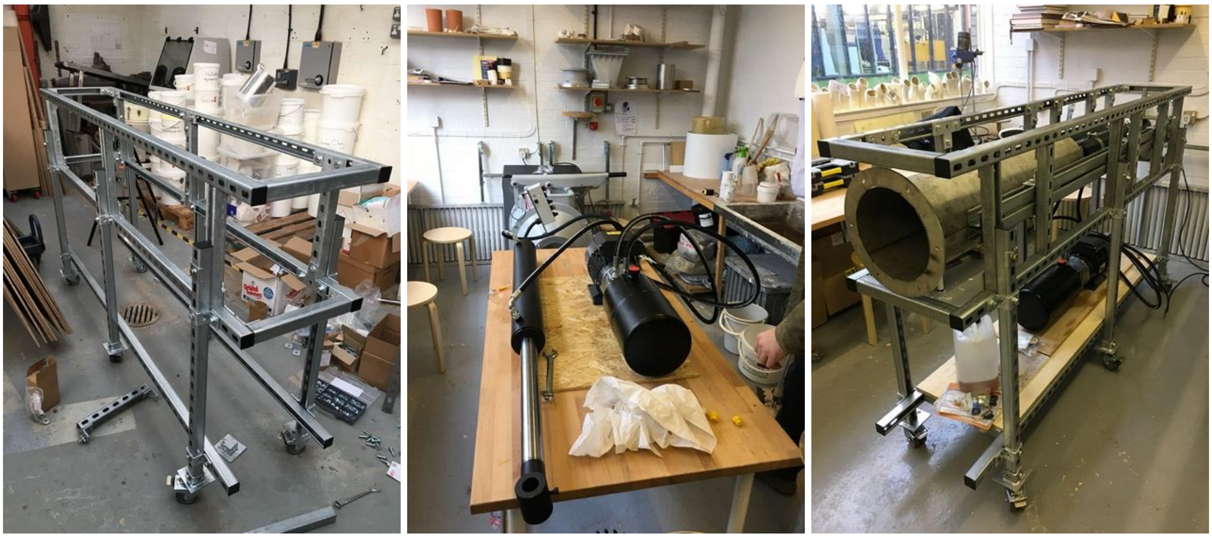

FIGURE 4. The construction of the piston-based extrusion machine used for this study. (Left) The basic frame constructed from Unistrut components. (Centre) The hydraulic power system. (Right) The completed extruder. (Photos: T. Jorgensen, 2019)

Extrusion die development

In terms of craft production, extrusion dies have traditionally been fabricated in fairly basic 2D profiles using plywood, polymers or steel plate (see Figure 1, centre left). In this study, a new approach was developed that used low-cost 3D printers to fabricate the main components of the extrusion dies (Figure 5). Since 3D printers can enable the creation of parts with almost limitless geometries, this approach opens up the fabrication of extrusions dies with new and complex geometries that would otherwise be very challenging (or costly) to produce with conventional fabrication methods. The use of 3D printers for this application has to date been largely unexplored, but it holds great potential in establishing low-cost workflows to translate designs into finished ceramic parts, a toolmaking process that is particularly relevant for individual makers or small companies.

FIGURE 5. The fabrication of extrusion dies using low-cost 3D printers. 3D printed parts were used in combination with bespoke laser-cut stainless steel brackets to enforce the die bridge, the part of the die found to be most prone to failure due to the high extrusion pressures. (Photos: T. Jorgensen, 2022)

Designing the extrusion dies so that they would generate a twisting, faceted texture in the extruded shapes posed particular challenges, but also generating significant opportunities for enhancing the understanding of the material behaviour of the clay in the extrusion situation. Extruded parts are primarily a result of the profile orifice of the extrusion die; however, the preceding geometries also have a significant impact on how the clay exists in this profile. Typically, tapered sides are used in the die design to encourage the clay to pass through the die and reduce the pressure needed for the process. However, in this case, the design challenge was related not only to reducing the pressure but also to designing a geometry that would generate the desired twisting effect in the extruded shapes. This effect was attempted by designing the dies with a geometry akin to that of gun barrel rifling. Furthermore, as the shapes would be produced as hollow tubes, the die design also had to include a *core* that would form the inner void of these tubes. This core had to be suspended by a bracket, commonly known as a *bridge*, around which the clay would travel and then re-form through a combination of pressure and die geometry. In this way, hollow sections could be produced. The bridge is the element most susceptible to bending or breaking due to the extrusion pressures, which in these investigations, typically reached levels of 30–50 bars of system pressure. Consequently, a *hybrid* construction approach was developed by combining the 3D printed parts with laser-cut stainless-steel elements to strengthen the bridge element.

A significant number of die designs were explored to produce the desired twisting effect, but achieving this artistic vision proved surprisingly difficult. Initially, highly tapered dies (with 10–30 degree sloped sides) were explored to help funnel the clay through the die, but it was very difficult to achieve any noticeable twisting with this die geometry. A number of other novel design approaches were tested to address this challenge, including a twisted bridge design (Figure 6, left) that aimed to encourage the clay to initiate a twisting behaviour *before* entering the tapered sections of the die. However, this approach did not produce any notable increase in the twisting effect. Another approach was to create a die with internal channels to facilitate integrated oil lubrication, but this delivered highly unpredictable results and was very challenging to operate (Figure 6, centre).

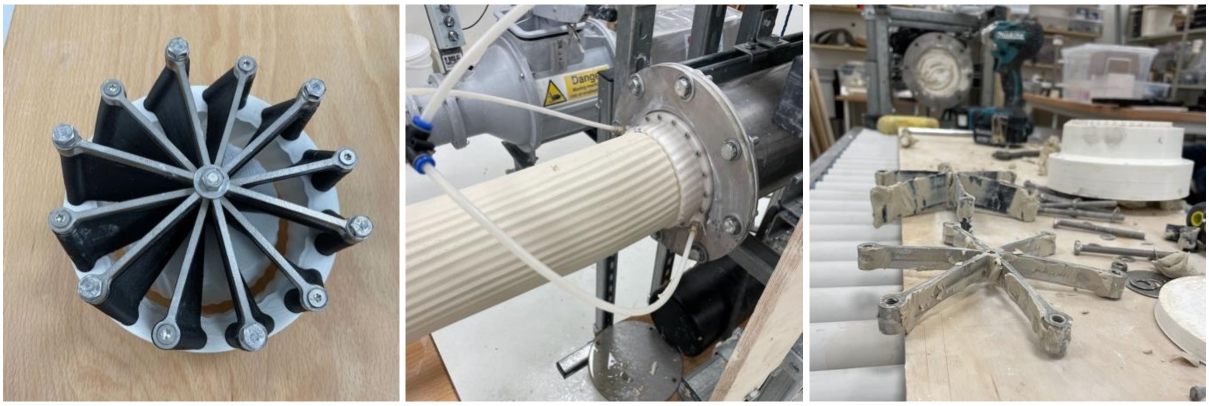

FIGURE 6. Unsuccessful extrusion approaches and faults arising from experimentation. (Left) Unsuccessful die design with a twisted bridge approach. (Centre) Experiment with an internally lubricated extrusion die. (Right) The extrusion force resulted in a deformed die bridge. (Photos: T. Jorgensen, 2022)

To develop an understanding of the reasons for the unsuccessful results from the initial experiments and address the challenge of achieving the desired twisting aesthetics, consultations were initiated with physicist colleagues. These discussions concerned particular aspects of the material behaviour of clay in the extrusion situation, including ‘shear-thinning’, ‘wall-friction’ and ‘strain-stress’ (Benbow & Bridgwater, 1993). Such interdisciplinary interactions helped the researchers develop a far better conceptual understanding of the test results, which helped to explain why it had been so challenging to achieve strongly twisted shapes. Based on the knowledge derived from these discussions, a new set of die designs were developed that achieved the most notable twisting effects. These dies were designed using a two-stage rifling approach, with the core die body having a 20-degree twist and initial taper of just 3 degrees. This 3-degree taper was informed by theoretically modelling the optimum taper in terms of minimising extrusion pressure (Leech et al., 2020). This core die element was combined with a nozzle designed with an enhanced twist of 30 degrees and no taper. It was speculated that these taper ratios would prevent shear-thinning behaviour, where the viscosity of a material decreases as it is subjected to shear forces. The minimal amount of taper with this design would normally be a potential issue in terms of the clay not having the opportunity to be forced together (after being split by the bridge arms), thereby creating poor re-joining of the clay body, resulting in seams and cracks. However, this issue was alleviated by raising the bridge on extended feet from the main die body (see Figure 7).

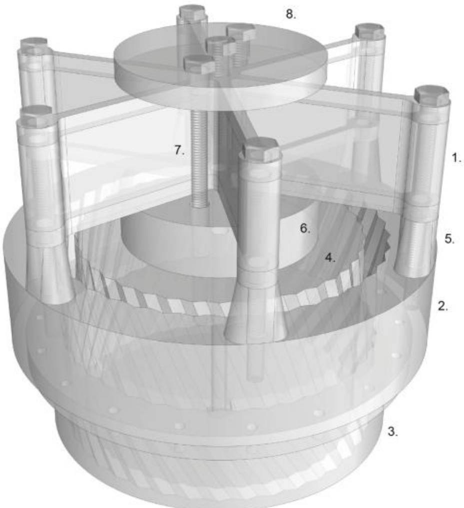

FIGURE 7. illustration of the most successful die geometry. (1) Bridge (3D-printed section sandwiched between laser-cut stainless steel profiles). (2) Die pressure plate (20-degree twist, 3-degree taper). (3) Nozzle (30-degree twist with no taper). (4) Inner core. (5) Bridge spacer feet. (6) Spacer disk. (7) Construction blots. (8) Construction support plate (stainless steel).

The challenges of clay characteristics used in the practical research

To enhance the aesthetics of the final output, porcelain was selected as the core clay body for the creative enquiry. This choice also made the research more challenging, since porcelain bodies have china clay (also known as kaolin) as the main constituent. Kaolin is decomposed granite that has remained in situ of its geological origins and known as a ‘primary clay’ (Fournier, 1992, p. 31). However, kaolin clay’s aesthetic qualities as a pure white mineral come with the downside of having reduced plasticity compared to other clay bodies, such as terracotta or ball clays, which are known as ‘secondary clays’ (Fournier, 1992, p. 247). ‘Special Porcelain’ (https://valentineclays.co.uk/product/special-porcelain) was selected as the main clay body in this research, as it has a small addition of the *bentonite* plasticiser, thereby combining the aesthetic qualities of porcelain with a somewhat improved level of plasticity. While a porcelain body makes the production of artefacts far more challenging, the lower plasticity level provides the potential for greater knowledge gain, since such a challenging medium would highlight any production issues and faults (see Figure 8).

FIGURE 8. Examples of the challenges of extruding porcelain. (Left) Splitting resulting from rapid drying. (Centre) Compression fractures. (Right) Gravity-induced cracks. (Photos: T. Jorgensen, 2022)

Creative research delivering innovations in response to technical challenges

The challenges faced in delivering the artistic vision in this research enquiry brought about a number of innovations not only with the extrusion die design but also other auxiliary elements of the workflow. The creative vision was to use a facetted texture in the extruded shapes as a particular aesthetic to highlight the nature (complex rheology) of the extrusion process. The use of this texture posed particular challenges in terms of handling the pieces as they emerged from the extrusion die. At the point of extrusion, the shapes are soft and highly susceptible to distortion from manual handling. In response to this issue, a novel external support approach was tested that used upholstery foam supports fixed to a fabric band on a roller conveyer (Figure 9). This approach delivered promising results that can be utilised for other creative investigations, although it prohibited the creation of the desired twisting texture.

FIGURE 9. Experiments with the use of upholstery foam supports fitted to a manual conveyor belt. (Photos: T. Jorgensen, 2022)

In addressing the challenge of handling the soft clay extrusions, an approach with *internal* support was also carried out. This approach explored the use of plastic tubes *over* which the porcelain shapes were extruded. After extrusion, the pieces were left to dry and harden to a consistency at which they could be handled without the risk of indentations. It was found that this approach caused an increased level of cracking (Figure 10).

FIGURE 10. Experiments with extrusion using internal support in the form of plastic pipes. In these tests, the extrusion die was fitted with a circular disk to ensure the plastic support pipes would stay in position during the extrusion process. The plastic pipes were heavily lubricated to ensure the clay would slide onto the support without sticking. (Photos: T. Jorgensen, 2022)

A third approach to address the challenge of manually handling the soft extruded shapes was to adapt the extrusion machine to operate in a vertical position. This approach proved to be the most successful, as it also enabled the extruded shapes to curve naturally according to variations in their rheology during extrusion (Figure 11). The design of an adaptive, multi-orientational piston extruder should be noted as an additional innovation outcome of the enquiry.

FIGURE 11. (Left and centre) Adaptation of the extruder machine to operate in a vertical position. (Right) A twisting shape being successfully extruded. Initial hardening of the shape was carried out with a hairdryer to enable handling. (Photos: T. Jorgensen, 2022)

Creative Outcomes

As previously highlighted, the creative vision was achieved by utilising combined knowledge resources to design the specific die geometry, which was then fabricated via 3D printing. The dies were used with the extrusion machine in a vertical orientation to allow the agency of the process to influence the aesthetics of the pieces. Following the extrusion, the pieces were manually trimmed with flat ends. Bases were created by placing the shapes on plaster bats and then pouring in liquid clay to seal one end of the hollow tube shape, thereby turning the hollow tubes into functional vases. Finally, the pieces were dried extremely slowly to prevent cracking. Once fully dry, the pieces were then glazed and fired.

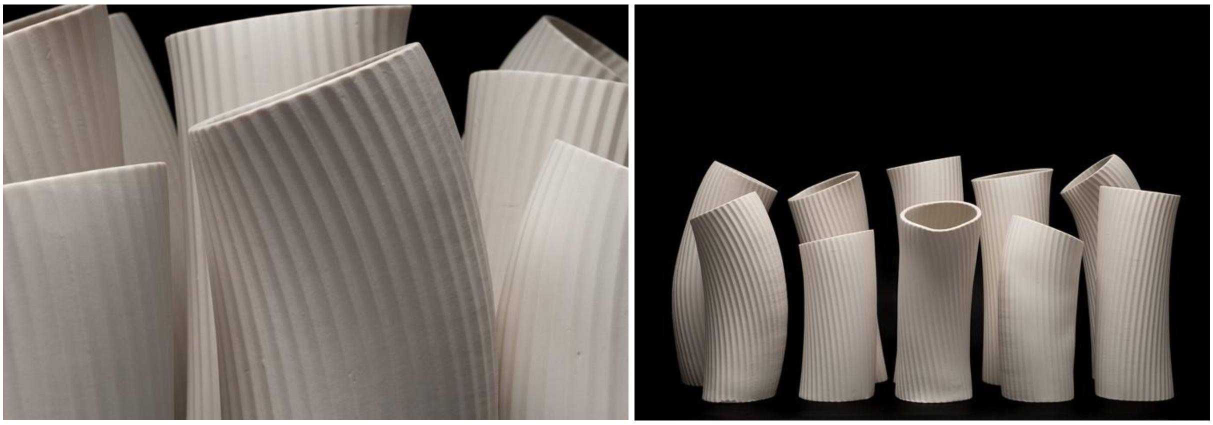

FIGURE 12. Collection of the finished fired porcelain vases. (Photos: F. Menger, 2023)

DISCUSSION

In reviewing and reflecting on the wider knowledge outcomes of the research, it may be relevant to revisit the research question of this enquiry: How can digital fabrication and knowledge about the complex rheology of the extrusion process be explored through creative investigations to develop a series of twisting ceramic vases?

The inquiry has revealed how unpredictable and challenging the rheology involved in clay extrusion can be; in particular, it has highlighted how plastic clay under pressure behaves more like a fluid than a solid medium, which is characterised as non-Newtonian behaviour. This was illustrated by the challenges the authors faced in terms of generating a twisting texture through the extrusion process, where the clay would have a tendency to travel *through* the die without 'responding' to the rifling, when the dies had a higher degree of tapering. At the outset, the researchers had limited knowledge of the scientific theories concerning the particular rheology that relates to clay extrusion. However, during the research, this knowledge was expanded through discussions with colleagues from scientific disciplines. The researchers believe that through this interdisciplinary interaction, knowledge of scientific theory provided an enhanced conceptual understanding that helped to interpret the results of the practical tests—an understanding that, in turn, informed the design approaches for the dies. These were design solutions that the researchers would most likely not have employed if they had only been informed by the tacit knowledge developed through their creative practice backgrounds. It can be argued that this research indicates good innovation potential; when some understanding of scientific theory is combined with the tacit knowledge base, it can be articulated as being a kind of *augmented* material understanding.

On a technical level, the research has delivered a number of knowledge contributions and innovations. These include novel ways of supporting soft extrusions, extrusion machine designs and approaches to the construction of extrusion dies. Most significantly, the study provides evidence for the usefulness of digital fabrication technology as a tool to facilitate innovation within an underutilised craft process, with the tangible outcome being the successful production of a body of creative work. The 3D-printed die parts held up extremely well to the high pressures from the extrusion process, with no significant wear detected. 3D printing has become an increasingly accessible and affordable development tool, but perhaps most importantly, the technology offers the potential for an extremely agile toolmaking workflow that facilitates fast iterative cycles of practical research to be carried out. As a research tool, 3D printing has very good capacity to support *inductive* research, where experimentation is foregrounded and theory predominately emerges from practice (Barrett, 2010, p. 6) or where practice and theory develop in close synergy, a process that Bolt (2010, p.29) has termed 'double articulation'. However, the use of 3D printing also enables a *deductive* approach, were theoretical knowledge is tested for validation (Cohen et al., 2007, p. 6). The use of new digital fabrication technologies for the toolmaking aspects in the research can be seen as significant enabling tools facilitating a hybrid, inductive-deductive research and innovation approach. The significance of toolmaking technologies in enabling innovation can also be seen referenced by Smiles (1863), who argued that the shift from hand to machine tools for toolmaking applications was a key enabler for the first industrial revolution.

This enquiry provides evidence that digital tools can offer innovation in an underutilised craft process. However, it may also be relevant to note that, as another outcome of this research, discussions are now underway with a local brick factory to utilise the results of this enquiry in an industrial context. This indicates that the new toolmaking capabilities of digital fabrication (low-cost 3D printing, in particular) can have innovation potential in both craft and industrial contexts and that craft makers with an augmented material knowledge have the capacity to contribute to innovation within both their traditional practices and industry.

ACKNOWLEDGEMENTS
We would like to extend our sincere thanks to the UK's Arts and Humanities Research Council (AHRC) for providing funding to enable this research.

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