A review of additive manufacturing for ceramic production

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Abstract

Purpose – In this paper, the authors aim to address the potential of mass personalization for ceramic tableware objects. They argue that additive manufacturing (AM) is the most adequate approach to the production of such objects.

Design/methodology/approach – The authors review the manufacturing of ceramic tableware objects, both traditional techniques and AM processes, and assess which available AM technologies are suitable for the research purpose.

Findings – The authors consider binder jetting and material extrusion as the most suitable processes for the production of ceramic objects to be integrated into a mass personalization system of ceramic tableware.

Originality/value – This paper provides an original overview of traditional and innovative techniques in ceramic manufacturing, exposing not only its differences but also its commonalities. Such overview supports the conceptual design of original equipment.

Keywords Product design, Additive manufacturing, Mass customization, Ceramic tableware, Mass personalization

Paper type Research paper

Introduction

Economic context

The competition in the world market for manufactured products has intensified tremendously in recent years. To swiftly bring products to market, many of the processes involved in their design, test, manufacture and market have been squeezed both in terms of time and material resources. Increasingly demanding consumers have pushed product design and manufacturing toward increased variety and complexity. At the same time, the life time of manufactured products and the lead-time required have been urged to decrease. The efficient use of resources calls for new tools and approaches.

The twentieth century featured a tendency toward a service-based economy, leading to deindustrialization. As a result, today's European economy is facing a growing challenge to compete with low wage regions, and therefore keeping, or bringing production back inside the Community. To regain competitiveness, the manufacturing sector must shift to high-tech industries:

- by moving from resource-based to knowledge-based manufacturing ("Treaty of Lisbon", 2007); and
- by moving from mass-produced single use products to new concepts of higher added value, custom-made, eco-efficient and sustainable products, processes and services (Gothenburg protocol, EU Commission, 2001).

Therefore, the manufacturing sector should invest in:

- intelligence and efficiency;
- high qualified workers;
- changing the way we think and fabricate products;
- being more creative;
- exploring new opportunities; and
- producing highly customized products that are difficult to copy.

A shift to mass customization, and particularly to mass personalization, its more elaborate version, is pointed as the way to achieve such objectives. As an emerging manufacturing paradigm, it diverges from the mass-produced, single use products by adapting them to their end-user.

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From craft production to mass personalization

Before the industrial revolution, the existing manufacturing paradigm was *craft production*, in which craftsmen would produce objects by hand or using hand-operated utensils. This meant that products took a long time to manufacture and at a high cost per unit. The industrial revolution in the nineteenth century meant a transition from handcrafted to *mass-produc*ed objects, leading to an exponential increase in production volume, as well as to a drastic decrease in cost per unit. However, this also led to a drastic decrease in variety. By contrast, craft production allowed for the product to be unique and adapted to its user's needs. The industrial machine would produce many more items in much less time, but they were all copies of each other (Hu, 2013).

This trend began to change in the 1960s with the introduction of lean production (Womack *et al.*, 1991). This manufacturing and management paradigm emerged from the automotive industry, which aimed at reducing waste to increase productivity. In lean manufacturing, products would be made-to-order, which meant that they could be adapted to that order before they were produced. Such approach, therefore, led to a new increase in product variety and paved the way to the next paradigm, mass customization, which would emphasize this tendency even more.

The concept of mass customization has been anticipated by Alvin Toffler in *Future Shock* (1971) and further developed in *The Third Wave* (Toffler, 1980). The new paradigm was coined "mass customization" by Davis (1987), but the methods to implement it were later systematized by Pine (1993). Since then, the concept has been upgraded. One most commonly cited definition of mass customization is the one by Tseng and Jiao (2001), as "producing goods and services to meet individual customer's needs with near mass production efficiency". A typical application of the mass customization paradigm is offered by sport shoes and automobiles manufacturers, which enable the customer to customize certain components from a defined set of colors. The color selection can be made online, through an automated configuration toolkit, which provides a visualization of the final product according to the customer's selection (Fogliatto *et al.*, 2012).

Recently, the paradigm of mass personalization has emerged, in which products can be tailor-made to individual-specific requirements. Mass personalization can be considered one step further from mass customization:

> [. . .] whereas both of these strategies are guided by the criterion of product affordability consistent with mass production efficiencies, the former (mass personalization) aims at a market segment of one while the latter (mass customization) at a market segment of few (Kumar, 2008, p. 536; Tseng *et al.*, 2010).

Also, personalization involves intense communication and interaction between two parties, that is customer and company (Piller, 2014). Examples of mass personalization include manufacturing of prosthetics, which are produced to fit specifically to one given patient. Typically, the region of the patient's body that will receive the prosthetic part is 3D scanned, so that the artificial part fits perfectly (Fiorindo, 1986/2012; Gibson *et al.*, 2010).

Mass personalization responds to the Gothenburg protocol twofold:

1 by creating custom-made products and services; and
2 by ensuring their sustainability.

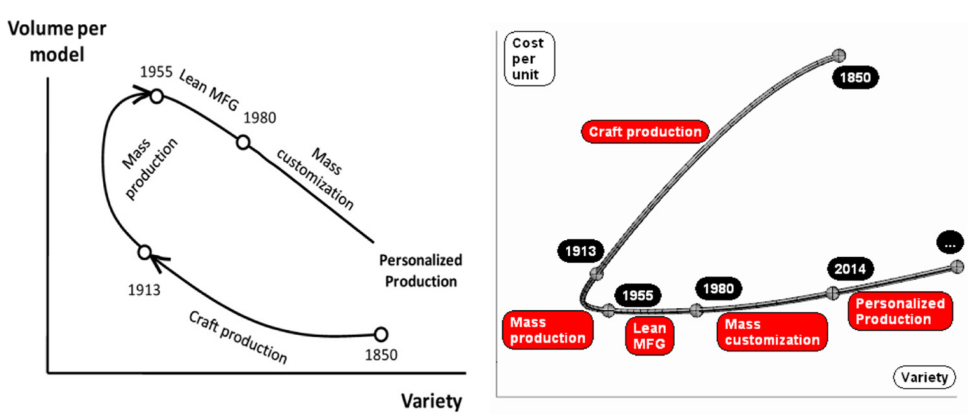
Mass personalization enables competitiveness by responding to current market demands. Today, consumers want to be treated as individuals – each having specific needs. Products are expected to be tailored to individual taste "built-to-order" but at prices comparable to those of standard mass-produced goods. Mass-personalized products are more sustainable than their mass-produced counterparts. In fact, some studies seem to indicate that a product that is adjusted to its user will be discarded later, reducing its environmental impact (Diegel *et al.*, 2010) (Figure 1).

Additive manufacturing toward mass personalization

Recent developments in digital fabrication, namely, additive manufacturing (AM) technology are enabling the adoption of mass customization and mass personalization strategies (Da Silveira *et al.*, 2001; Hu, 2013, p. 6; Piller, 2004; Reeves *et al.*, 2011). AM is revolutionizing the manufacturing industry by enabling the rapid, flexible and cost-efficient design and production of products across different applications and industries (Wohlers, 2014) while featuring some important characteristics:

- AM is sustainable because it typically produces less waste than, for instance, subtractive manufacturing techniques (Diegel *et al.*, 2010). Also, AM allows for a product to be

Figure 1 Left: volume variety relationship in manufacturing (Hu *et al.*, 2011) and Right: relationship between cost per unit and variety (used with permission)



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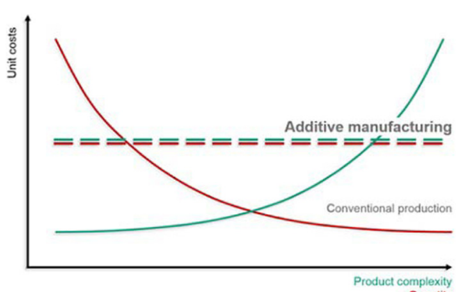
manufactured virtually anywhere as long as there is raw material available because design is shifting to digital data that can be accessed anywhere in the world in a matter of seconds. This reduces the product's transportation costs, as well as its environmental impact.

- AM offers complexity for free (Hague *et al.*, 2003), as there is no increase of cost when comparing the AM of a complex component with a simple one. Therefore, AM technology can be used to produce almost any shape.
- AM also offers individuality for free (Dillenburger and Hansmeyer, 2013) because the cost of manufacturing a batch of products that are different from each other is the same as if they were equal. In this case, cost depends solely on quantity of material not on variation of shape (Figure 2).

Motivation and methodology

The motivation for this paper is the mass personalization of ceramic tableware. There is an interest for personalization in this sector as previous studies and projects have shown (CM Alcobaça, 2009; Museros *et al.*, 2004). However, only a few of these have tapped the potential of AM as a production system and only for relatively simple shapes (Huang and Hudson, 2013). In fact, manipulation of the curved shapes typically found in ceramic tableware is all but straightforward. We aim at delivering a sophisticated system that enables the consumer to personalize his or her own ceramic tableware set, through an extended design space in terms of both shape and decoration, while maintaining a captivating experience. Using such a system, each consumer can generate a unique solution according to his or her own needs and taste, and hence, the expression "mass personalization" of ceramic tableware is used instead of "mass customization", according to the definition discussed earlier.

Figure 2 Additive manufacturing: complexity and individuality for free



Source: Aghassi and Witzel (2014), used with permission

The implementation of a mass personalization system (Figure 3) implies the articulation among three sub-systems: design, computer and production, adapting a model proposed by Duarte (2008) for implementing mass customization. A design system based on shape grammars (Stiny and Gips, 1972) is being developed to insure consistent design features amongst all the elements in the set, or collection, as well as to enforce constraints derived from the manufacturing process or ergonomic design guidelines (Castro e Costa and Duarte, 2013). The computer implementation of the design system must cope with the challenges that derive from assigning the role of designer to end-users, who might easily become overwhelmed by the "white canvas syndrome". And finally, the production system must be capable of materializing whatever shape is designed by the end-user. Such need for formal flexibility calls for the use of AM.

In this paper, we shall focus on the production system of personalized tableware. The first step was to conduct a technology survey on the state-of-the-art concerning additive technology, specifically technology that has been used for the production of ceramic objects. The solutions identified in the survey have been analyzed according to criteria stemming from the requirements of the personalization system to determine which technology would be more suitable for our purpose.

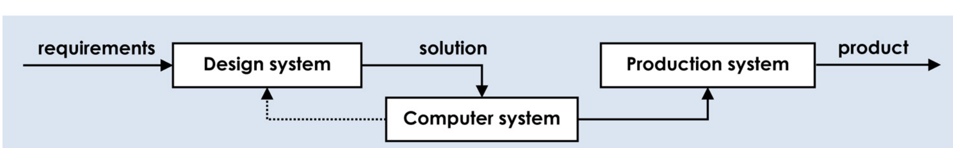
Manufacturing of ceramic objects

Before focusing on the existing AM solutions, we present an overview of handicraft techniques for producing ceramic objects. Then we look at how these traditional techniques were adapted to industrial manufacturing. Finally, we focus on current AM technology applied to ceramics, with an emphasis on consumer products such as tableware.

Ceramics manufacturing process

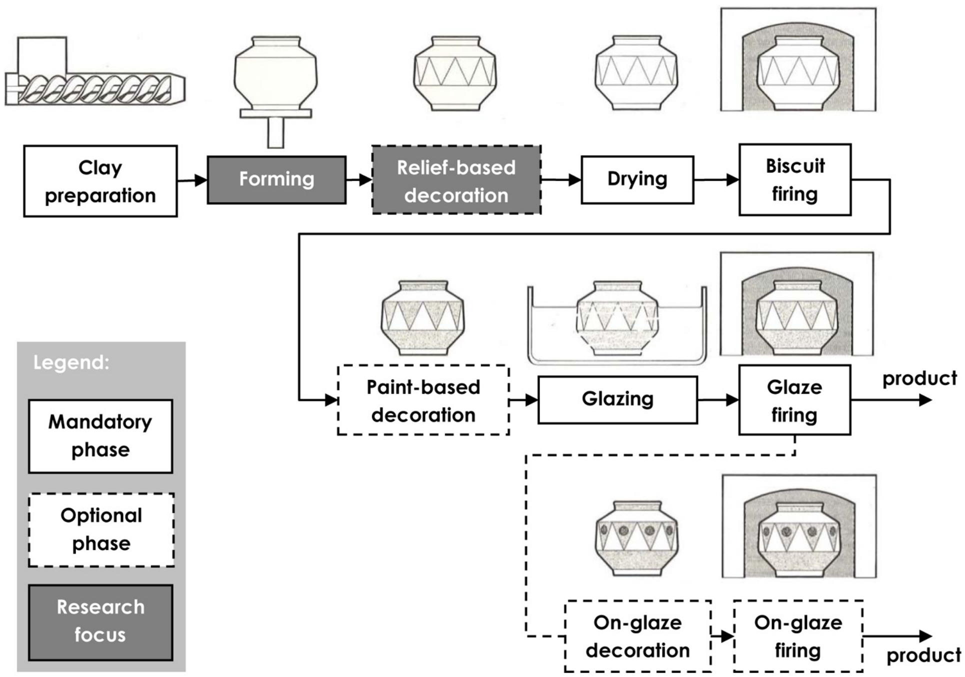
Either in handcrafted or industrial manufacturing, from simple vases to geometrically complex and intricately decorated sculptures, the making of every ceramic piece goes through a similar sequence (Figure 4): after preparing the clay, and while it remains in its plastic state, the ceramic object is given its shape, as well as its decoration, if based on reliefs (three-dimensional decoration). The object is then dried, and fired a first time, resulting in what is called the biscuit. The biscuit is then covered with glaze, which grants it the shiny look and smooth texture that is typical of tableware ceramics. If the piece is to be painted or decaled, such two-dimensional decoration is applied before the glazing. After glazing, the ceramic object is fired once more. For plain ceramic tableware, without any decoration, the manufacturing process

Figure 3 Mass personalization implementation model



Source: Adapted from Duarte (2008), used with permission

Figure 4 Typical ceramic manufacturing process



Source: Adapted from Hamilton (1974), used with permission

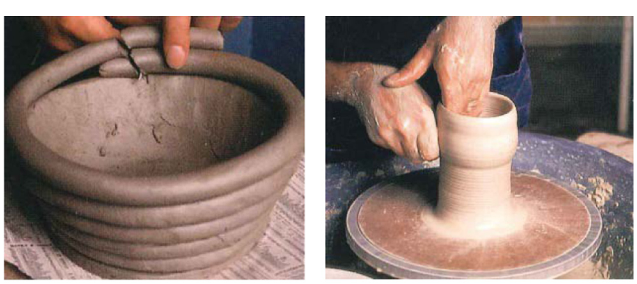
would stop here. Alternatively, the piece may be given on-glaze decoration, after which it must be fired one last time.

Because the objective of the mass customization system is to manipulate the shape of the tableware elements, 2D-decoration after biscuit firing and on-glaze decoration will not be addressed, and we will focus our attention on the forming or modeling phase.

Handicraft ceramic modeling

There are several traditional techniques for modeling ceramic objects, namely, tableware elements. Hand methods of forming clay include coiling and throwing (Figure 5). Coiling consists of making coils out of clay and stacking them on top of each other. The surface of an object made by coiling is revealing of the process used and is typically smoothed by hand or using proper utensils. Throwing is probably the most recognizable of the handicraft shaping techniques, in which hand pressure is applied on a ceramic piece that is rotating on a device, the potter's wheel (Hamilton, 1974).

Figure 5 Handicraft ceramic modeling techniques: coiling (left) and throwing (right)



Source: Quinn (2007) © Quarto Publishing plc, used with permission

Moulding methods of forming clay include pressing and slip casting (Figure 6). These methods make use of plaster moulds that hold the negative shape of the desired object. Pressing consists of manually pressing clay in its plastic state against the mould, so its shape is transferred to the clay. In slipcasting, a suspension of clay in water – the slip – is poured inside the mould (Hamilton, 1974). Other moulding methods include jiggering and jolleying (Figure 6), which consist of forcing a piece of clay to shape against a plaster mould through rotation, similarly to throwing on the potter's wheel. This technique is suitable for producing revolution-based open ceramic pieces, such as circular plates (jiggering) and bowls (jolleying) (Quinn, 2007).

Industrial ceramic modeling

Some of these traditional techniques were adapted into an industrial context, boosting their productivity. Roller

Figure 6 Mould-based traditional techniques, from left to right: pressing by hand (Hamilton, 1974), slipcasting, jiggering and jolleying (Quinn, 2007 © Quarto Publishing plc; used with permission)

machines make use of a heated metallic mould and a plaster die, which rotate while pressing a piece of clay into the desired shape. Roller machines allow for low production costs per unit, making them ideal for producing large batches (Rado, 1988). Industrial slip casting is not very different from the traditional handicraft version. Of all industrial techniques, slip casting is the one that enables greater freedom of shape. Therefore, such technique is typically used for smaller production batches (Rado, 1988). Plastic pressing, or "ram" pressing, and isostatic pressing, or dust pressing, consists of shaping a piece of clay between two permeable plaster dies that are pressed together. These techniques are typically used for shaping non-round objects, which would otherwise be produced in roller machines (Rado, 1988). Therefore, in terms of shape, pressing is more flexible than roller making, but less than slip casting.

All these industrial methods are designed for mass production of ceramic objects. Slip casting, which is typically used for producing the smallest batches, is considered to be profitable for a minimum of a few hundred pieces sharing the same mold. Such quantity is still too large for mass personalization. Even if a customer is buying a large dinner set, it is very unlikely that it will contain more than 24 elements of the same type, and some of them, such as trays or tureens, will be no more than three. As such, for producing such small batches, we should look into current AM techniques.

Additive manufacturing applied to ceramics

Along with the recent developments of AM technologies, especially with the rise of consumer-oriented equipment, the term "3d printing" is often used to refer to those technologies. In fact, a Google search for "3d printing" produces more results than one for "additive manufacturing" (Wohlers and Caffrey, 2014). Nevertheless, for the purpose of this research, the industrial standard is used. Therefore, and according to ASTM International Committee F42 on Additive Manufacturing Technologies, AM is defined as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methods (ASTM F42 Committee, 2012). Also, according to the ASTM F42 Committee, AM processes can be sorted into seven categories:

1. *Material extrusion*: an AM process in which material is selectively dispensed through a nozzle or orifice;
2. *Material jetting*: an AM process in which droplets of build material are selectively deposited;
3. *Binder jetting*: an AM process in which a liquid bonding agent is selectively deposited to join powder materials;
4. *Sheet lamination*: an AM process in which sheets of material are bonded to form an object;
5. *Vat photopolymerization*: an AM process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization;
6. *Powder bed fusion*: an AM process in which thermal energy selectively fuses regions of a powder bed; and
7. *Directed energy deposition*: an AM process in which focused thermal energy is used to fuse materials by melting as the material is being deposited.

Except for directed energy deposition, every one of these processes has been applied to the manufacturing of ceramic objects, and most of them are commercially available. A technology survey was conducted to assess the availability and advantages of each of these processes.

We have clustered the technologies and available equipment according to its suitability for producing tableware. In fact, most of the AM technologies are applied to ceramics for the production of precision components, such as electronics, etc. Two processes emerge as the most adequate for our purposes: binder jetting and material extrusion.

Material extrusion

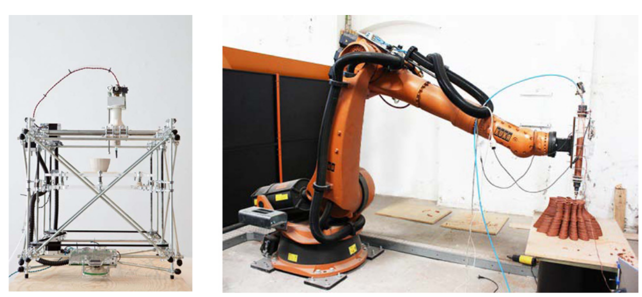
Material extrusion is probably the best-known AM technology. The expiration of patents on material extrusion, namely, of fused deposition modeling, is behind the current dissemination of low-cost 3D printers (Wohlers and Caffrey, 2014). Extrusion of ceramic material has been explored both in academia and in design practices. Different projects have studied the constraints and explored the potential of extruding ceramic paste through a nozzle to build objects. In a way, these approaches invoke the traditional techniques of coiling and throwing.

Belgium-based design practice Unfold developed a system from a RepRap 3D printer (Unfold, 2009). Originally, the RepRap machine was designed to extrude polymeric materials, just like so many of the 3D printers that have emerged in recent years. By modifying the extrusion head to extrude white clay, they have managed to produce ceramic objects from digital models through AM (Figure 7, left). Ceramics artist and educator Tom Lauerman also made use of a RepRap printer, the Prusa i3, for producing ceramic objects (Lauerman, 2014).

A similar approach was tested at IAAC by a team of students in their project Fabclay (Jokić *et al.*, 2012). In this project, a robotic arm was used to control the position of the extrusion head, depositing several layers of clay, thus producing the intended ceramic object (Figure 7, right). Despite the many degrees of freedom provided by the use of a robotic arm, in this project, this equipment was used to replicate the movements of a Cartesian 3D printer, i.e. XYZ translation. In this case, red clay was extruded instead of white clay, which was used by Unfold.

Recently, ceramic designers experimenting with AM have moved from Cartesian-style to delta-style printers. In the vast

Figure 7 From left to right: extrusion of white clay objects by Unfold, Belgium (Photo courtesy of Unfold, ©Z33, photo by Kristof Vrancken; used with permission) and of red clay object by Fabclay (2012)



majority of 3d printers, the mechanism for positioning the extrusion head corresponds to a Cartesian manipulator, in which joints correspond to the X, Y and Z Cartesian directions (Craig, 1989). On the other hand, delta-style printers' kinematic configuration corresponds to a linear delta robot (also known as Linapod), in which the extrusion head is positioned by three vertical linear actuators (Merlet, 2006). Because the actuators are identical, such a machine is actually easier to implement (Boer *et al.*, 2012). Both US-based Keep (2013) and The Netherlands-based van Herpt (2014) have used a delta printer to extrude clay and produce large ceramic objects (Figure 8).

Alongside these projects, equipment suppliers have developed ceramic extrusion machines based on the delta robot configuration. Recently, two ceramic 3D printers have entered the market: PotterBot (DeltaBots, 2015) and DeltaWASP 20 40 (WASP, 2015). The DeltaWASP machine works in a very similar way to the machines used by both Jonathan Keep and Olivier van Herpt. In fact, previous collaborations between WASP and Jonathan Keep (Keep, 2014) suggest he operated actual prototypes of the DeltaWASP. In this machine, the delta robot positions the extrusion head along the successive layer paths that build the object. This machine can produce objects as wide as 200 mm and up to 400 mm tall. The Potterbot, on the other hand, features a static extrusion head, whereas the build platform and the actual object are manipulated by a delta robot located under the build platform. Potterbot can print objects up to 17 inches (431.8 mm) tall and 8.75 inches (222.25 mm) wide.

Material jetting

France-based company CeraDrop supplies a machine called CeraPrinter, which produces Printed Electronics through material jetting (Ceradrop, 2013). The system is able to deposit a wide range of inks although none of them are ceramic-based, despite the name suggestion. However, the system is able to print on ceramic substrates, but it is unsuitable to produce ceramic objects. In fact, the maximum dimensions of the produced parts must fit in in a 305 mm wide, 10 mm thick square, dimensions which are adequate for electronics but not for manufacturing tableware. Nevertheless, CeraPrinter is the only surveyed equipment using material jetting technology and ceramic materials and therefore was included in this analysis.

Binder jetting

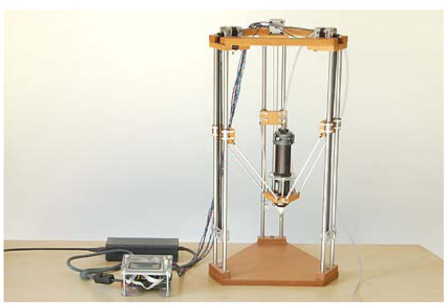
In recent years, several research teams have been exploring the possibility of using the binder jetting principle for manufacturing ceramic objects, either on the hardware side (Hoskins, 2012; Universidade de Aveiro, 2013) or on the material side (Figulo, 2013; Tethon 3D, 2014). The common starting point for these projects was the 3D Printer, a machine developed at MIT in the 1990s, that later justified the spin-off of ZCorporation and is now part of the 3DSystems product family. Originally, the 3D Printer produced objects by jetting a cyanoacrylate-based binder onto layers of a plaster-based powder. By using the same process but replacing the plaster-based material with ceramic powder, these teams have been able to produce detailed green ceramic objects, which can then follow up on their typical production process, through firing in the kiln, glazing, etc. (Figure 4).

Currently, ceramic binder jetting appears to have moved from the research to the commercial domain. In the 2014 edition of Consumer Electronics Show, US-based company 3DSystems announced CeraJet, a "3D printer" that produces ceramic objects. This equipment is allegedly suitable for producing large ceramic objects, such as tableware although the dimensions of its build envelope have not been revealed. At the time, its commercialization was announced for the second half of 2014 although according to information on the company's website it is postponed to 2016 (3DSystems, 2014). 3D systems first entered the world of ceramics in December 2013 by acquiring Figulo, a Boston-based company that produced ceramic parts using binder jetting (Wohlers and Caffrey, 2014). Shortly after, 3D systems announced they would commercialize the CeraJet ceramics 3D-printer.

Lamination

US-based company CAM-LEM applied lamination technology to the production of ceramic and metal components for microfluidic applications and technologies through a machine called CL-100 (CAM-LEM, 2005). According to the company, the maximum build size is a 150-mm cube. However, no further technical information is available on the company's website. Nonetheless, both the explanation of the process and samples on the website suggest that this technology would be more suitable for objects featuring vertical, rather than oblique or curved, surfaces. As

Figure 8 From left to right: extrusion of tall ceramics objects by Keep (2013) and by van Herpt (2014), used with permission



such, it would most likely be inadequate for producing tableware.

Vat photopolymerization

Several companies are currently supplying equipment for AM of ceramics through vat photopolymerization.

CeraFab 7500 is supplied by Austria-based company Lithoz. According to the company, this printer is suitable for producing high-performance ceramic objects, namely, cost-effective prototypes, small scale series and complex parts, through its proprietary LCM technology (Lithoz GmbH, 2012). The build envelope is rather small – 76 × 43 × 150 mm.

CeraMaker applies laser stereolithography to ceramics, and it is supplied by France-based company 3DCeram. According to the company, this printer is particularly suitable for manufacturers of ceramic parts, integrators or end-users of ceramic parts, players in the luxury or biomedical industries but also in the industry in general (3DCeram, 2014). In comparison with the previous example, the build envelope is larger – 300 × 300 × 110 mm.

Italy-based company Digital Wax Systems is launching the DWS XFab, which applies laser stereolithography to several materials, including a "ceramic nano-filled" composite (Digital Wax Systems, 2014), which is unsuitable for producing tableware. This machine is marketed as a consumer-oriented 3d printer, costing around US$5,000 (Wohlers and Caffrey, 2014). Its work area is limited to a cylinder that is 180 mm wide and tall.

K20 is a piece of equipment that applies laser stereolithography to composite materials of ceramics and metal supplied by France-based company Prodways (2013). The maximum build area is a box of 150 × 560 × 150 mm. The focus on composite materials suggests that such equipment might be less suitable for producing mono-material ceramic objects.

Powder bed fusion/sintering

Phenix, a France-based company, recently acquired by 3DSystems, supplies equipment for laser sintering of metal and ceramic powders (3DSystems, 2013). The build envelope for the most capable machine that deals with ceramics, the ProX-200, is 140 × 140 × 100 mm.

Chinese company Wuhan Binhu develops sintering systems for several different materials including three ceramic powders (Wohlers and Caffrey, 2014). The maximum build size for producing ceramic parts is a 500 mm square, 400 mm high. Although this build envelope is large enough for producing most of the elements of a complete tableware set, typical costs for sintering technology suggests that this option is not competitive.

Directed energy deposition

During this survey, we have not found any application of directed energy deposition in ceramics.

Comparative analysis of additive manufacturing technology

From the survey presented above, and as summarized in Figure 9, we verify that most of the AM processes and equipment are focused on the production of high-performance precision parts, compromising their suitability for production of tableware.

Figure 9 Summary of additive manufacturing equipment for ceramics

Process	Supplier	Equipment	Dimensions (wxlxh mm)			Equipment cost *
Material extrusion	WASP	DeltaWASP	200	200	400	€ 2,370
	DeltaBots	PotterBot	222	222	432	€ 3,175
Material jetting	CeraDrop	CeraPrinter	305	305	100	€ 175,000
Binder jetting	3D Systems	CeraJet	N/A	N/A	N/A	€ 9,200
Lamination	CAM-LEM	CL-100	150	150	150	N/A
Vat photo polymerization	Lithoz	CeraFab	76	43	150	
	3DCeram	CeraMaker	300	300	110	€ 290,000
	Digital Wax Systems	DWS Xfab	180	180	180	€ 5,000
	Prodways	K20	150	560	150	
Powder bed fusion	3Dsystems (Phenix)	ProX-200	140	140	100	€ 200,000
	Wuhan Binhu	HRPS-IV	500	500	400	€208,000
Directed energy deposition		N/A				
Reference for dimensions		(standard dinner plate dimensions)	270	270	160 (standard teapot height)	

* estimated cost values, either from quote requests to suppliers or press releases; values have been normalized to euro (€)

The first limitation is set by the dimensions of the building envelopes. A standard dinner plate, for example, which typically measures 27 cm in diameter and 3 cm in height, would not fit in more than half of the surveyed machines. The ones where a plate would fit could not accommodate a standard 35 cm tray or a teapot, which can be 16 cm tall. The only exception is the Laser Sintering equipment from Wuhan Binhu.

The second limitation is set by the cost of printing tableware elements, namely, of the printing materials. In fact, some of the contacted equipment suppliers actually considered it unsuitable for producing ceramic tableware elements, mainly because the ceramic materials are mostly alumina-based. These materials are developed to meet demanding technical characteristics and therefore expensive when compared to the material typically used for producing tableware.

In general, we conclude that most of the commercially available solutions are unsuitable for producing mass customized tableware. Two processes, nevertheless, stand apart from these technologies: binder jetting and material extrusion.

Binder jetting is currently being established as the *de facto* standard for ceramic AM. In fact, several print-on-demand companies (Shapeways, i.Materialise, Ponoko and Figulo, now owned by 3DSystems) are outsourcing this technology to supply ceramic "3D prints" to clients over the internet. However, the cost of such pieces is still high. As with the 3D Printer, also supplied by 3DSystems, the materials to be used with the CeraJet are likely to be proprietary – and therefore quite expensive if the material price range is similar to the original 3D printers. Printer owners might try their own materials but at the risk of damaging the printer, and because the used materials were not recommended by the equipment manufacturer, its warranty would be void. Therefore, using this equipment in the production system of personalized tableware might represent a disadvantage; for a company adopting such an approach would depend on a single supplier and imply rather high material costs.

The material extrusion approaches covered earlier handle this particular problem quite well. In all projects, the extruded material is a ceramic paste mixed by the machine's user. This mix must be fine-tuned in terms of viscosity and others properties, but when the right mix is achieved, it can be replicated. This "open-source" approach sets material extrusion apart from the other AM processes.

However, ceramic extrusion presents challenges that must be addressed. In all of the projects referred to, we could identify two factors that could be improved. The first one is the expression of the layers in the manufactured objects. Such texture reveals the nature of the layering process used to make the object. Although in some cases this texture can be desired or even taken advantage of by the designer, it would be important to avoid it in other cases. The second factor relates to the shape of the produced object. In fact, all printed objects possess a somewhat vertical geometry. Although not stated by the authors, this can be identified as a way of avoiding the need for support structures. Consider that we wanted to manufacture a dinner plate using any of the extrusion techniques mentioned above. Without using a supporting structure, the plate would likely collapse during its manufacturing process. However, supporting structures should be avoided because they imply more material consumption and require time for their removal. Also, removing support structures usually leads to minor imperfections on the model (Smyth, 2014). Therefore, it would be desirable to overcome this limitation. In the 3D-printing community, the so-called 45-degree rule is often used to address this problem. This rule-of-thumb states that "overhangs that are greater than 45 degrees will need support material or you need to use clever modeling tricks to get the model to print" (France, 2013). The rule suggests that support structures can often be avoided through clever geometry.

Conclusion

In this paper, we have addressed the potential of mass personalization for ceramic tableware. We have argued that AM is the most adequate approach for the production of such objects. Furthermore, we have reviewed the manufacturing of ceramic tableware objects and assessed which available AM technologies would be suitable for that purpose. Based on this assessment, we are developing a conceptual design of a machine for the production of ceramic tableware objects through material extrusion. The design of the machine is based on the experiments with clay extrusion described above, and it aims to overcome what has been identified as the two major challenges in clay extrusion: the need for supporting structures, and visible layer expression. The design, development and testing of such machine will be the subject of a future publication.

The main objective of this research is to implement such a mass personalization system in an industrial context for which contacts with companies in the ceramic sector have been established. Under such partnership, we expect to build a prototype of the machine under development to test it and assess its suitability for the manufacturing of personalized ceramic tableware.

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