The Future of Small-to-Medium-Scale Production of Ceramics: The Use of Thermoplastic Polyurethane 3D Printing to Produce Molds in Educational Institutions

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The Barcelona Conference on Arts, Media & Culture 2022
Official Conference Proceedings

Abstract
Using 3D printers to create molds for ceramics arts and industries is one of the new techniques influencing these creative fields. The role of thermoplastic polyurethane (TPU) in the creative industries has received increased attention across a number of disciplines in recent years. It is well known that TPU is a flexible, durable material, and it is considered a suitable material to create ceramic mother molds because of its abrasion-resistant thermoplastic nature. However, the most important reason to use TPU in ceramic plaster molds is that the plaster can be extracted from molds very easily and all the copies will be typically similar to each other. There is an urgent need to address the problems associated with using this technique in ceramics educational institutions. The aim of this paper is to experimentally explore the use of TPU 3D printing in developing ceramic molds and draw the attention of mold-makers to the best practices to solve these challenges.

Keywords: TPU Molds, Ceramics, Art Education

Introduction

Thermoplastic polyurethane (TPU) was invented by Lubrizol for commercial use in 1959. A large and growing body of literature has since investigated the physical characteristics of TPU material, which is usually categorized between rubber and plastic (Nihal et al., 2019). However, it is possible to customize TPU from a softness that is similar to rubber to a hardness like rigid plastic. Because of its thermoplastic nature, its extreme flexibility and exceptional load capacity mean that this type of material has many benefits in the design field, including ceramics. TPU can be processed in the same manner as in traditional thermoplastic manufacturing, but the most useful methods in recent times have been printing via SLS or FFF 3D printing machines (Bates et al., 2016).

A major advantage of using TPU is that it is abrasion-resistant, meaning that the plaster can be cleaned effortlessly between castings. It has also been selected by manufacturers for its reliability and validity in terms of chemical resistance, and because of that, this material is mostly considered the best for industrial use. For ceramicists, however, the most important characteristic is flexibility, which allows the maker to remove plaster from the mold very easily. This can explain why ceramicists prefer (low-temperature performance) TPU in plaster mold-making. In general, we can summarize TPU's benefits being its flexibility, softness, optical clarity, chemical and hydrolytic resistance, approved skin contacts safety, bio-based and recyclable composition, easy-to-extrude nature, antimicrobial resistance, and abrasion, impact, and puncture resistance. TPU has become the most preferred material to produce ceramic molds because of its flexibility in terms of offering great mechanical properties, such as high tear and tensile strength. The TPU material opens up a world of unlimited possibilities for countless industries and products, including shock absorbers, cables, hoses, mobile phone covers, automobiles, footwear, functional prototypes, tires, and ceramic molds.

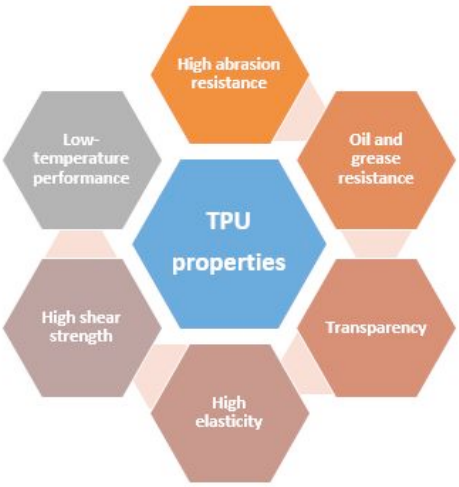

Figure 1: TPU Properties (Bjorn Thorsen, 2020)

Technically, when using FDM printing technology, the maker has to apply a thin layer of glue to the print bed before printing models with TPU. Because of the nature of these probable materials, it is also suggested that the extrusion nozzle must reach a temperature between 210 ºC and 235 ºC to melt the filament. In fact, a temperature of at least 200 ºC is essential to melt the material, so most 3D printing machines will not start creating the object before reaching this temperature. Rather than applying the normal technique of using a single extrusion nozzle to print TPU, some researchers developed an innovative method for the direct fabrication of multiaxial force sensors to create 3D printed objects using flexible materials (Kim et al., 2017).

Recently, one of the best examples of using the 3D printing technique was created by designer Dov Ganchrow in his project V300. According to Ganchrow, “The V300 project was a conceptual project looking at small-to-medium scale ceramics production and making use of 3D printing in the updating of the manufacturing process. A 3D printed ‘mother mold’ (actually only the part of the mold that has the end-products geometry is printed, the constant forms are still injection molded) that has plaster poured into it to create a product that in the ceramic industry is called a ‘plaster mold’. The plaster mold is filled with slip – a fluid ceramic material and when this solidifies, (and after firing) we have a ceramic end product such as a vase. So basically I designed a mold that makes molds, hence the term ‘mother mold” (Bentur, 2017).

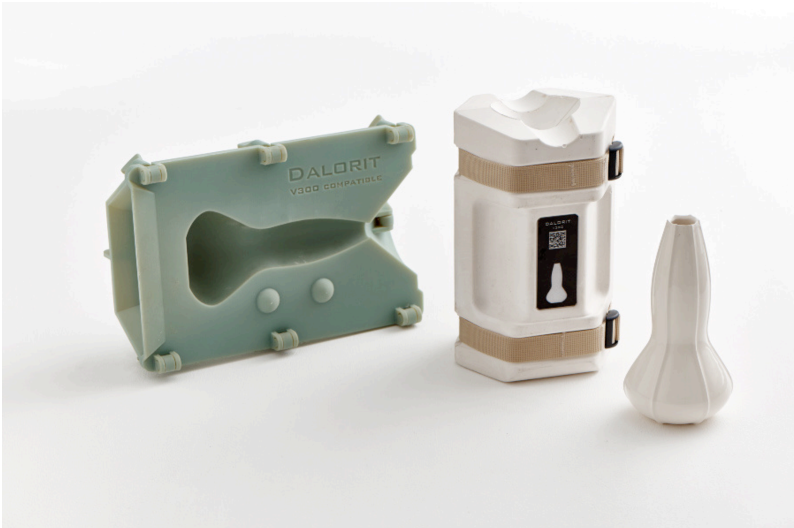

Figure 2: V300 Molds Production System by Dov Ganchrow, photo by Moti Fishbain (Leo Lane, 2017)

Slip Casting in Ceramics Arts and Industries

Slip casting is a process of using clay in liquefied form that is poured into a mold, which is usually made of plaster of Paris. Slip casting liquid becomes stiff when attached to a plaster mold’s internal walls (Martin, 2007). A considerable amount of literature has been published on slip casting from the 19th century. It was not until the late 1820s that historians considered slip casting worthy of scholarly attention. According to Frith (1992), Simeon Shaw was the first to write about the slip casting technique in 1829. Three years later, the Rev. Dionysius published more details about the technique of slip casting with clay slurry in plaster molds. According to the description of this technique, the ceramic piece can be formed when the mold absorbs water from the casting slip (Raffie et al., 2018). The process of casting clay in plaster molds was actually invented many centuries ago, and classic publications of the early 20th century documented this process regarding ceramics industries. For example, Walter Shearer (1928) mentioned in his paper that producing a desirable flowing quality in a slip is proposed as a means of controlling its casting quality. In addition, Schramm (1934) confirmed that the casting behavior of clay in plaster molds depends on the properties of the mold, the slip, and the casting design shapes; in fact, the water retention of the casting is of particular significance, and experiments reveal how this depends on the nature and condition of the slip as well.

Experimental Stage 1: Designing the TPU Mold

In this study, TPU 95A flexible material was commercially obtained from eSun and used to form the mother molds for ceramic casting. According to its technical data sheet, this material degrades in the range of 240–250 °C. It is also mentioned that this TPU has a density of 1.19 kg/dm, a hardness of 93 Shore A, a tensile strength of 40 MPa, and elongation at break of 550%. The manufacturer confirmed that at the end of printing of the final product, the mother mold will be opaque black, a very soft texture, extraordinarily elastic, and have high resilience. Table 1 below shows the ingredients of the filament according to the safety data sheet:

Ingredient Name	Content (%)
C6H1004	50%
C4H7NO	30%
C4H1002	20%

Table 1: The ingredients of the filament used in this project according to the eSun safety data sheet

Using AutoCAD, the forms of the ceramic mother molds were created in two pieces. The logo of Sultan Qaboos University (SQU) was added to use the final copies of the ceramic pieces in the ceramic's laboratory for glazing tests in the future. The thickness of the surrounding walls of the molds was 3 mm to guarantee the easy extraction of gypsums molds from the TPU mother molds, and the remaining walls of the TPU mother molds were at a right angle (90°) while standing after pouring the gypsum slip. According to the 3D printing invoice sheet, the quantity of TPU that was used to complete both mother mold parts was 650 g, and the period of time to print them was 30 hours. At the end of the printing process, the final two pieces were as shown in Figure 3, and they were ready for the plaster stage.

Experimental Stage 2: Producing Plaster Copies

After the 3D printed TPU mother mold was designed in the first stage of experimentation, it was ready for making some copies of the final plaster molds. It is well known that molds for ceramics made from plaster absorb moisture from slip casting clay. This type of mold usually causes the clay to shrink after forming in the plaster mold and makes it easier to remove the molded pieces.

Plaster of Paris was used in these research experiments. This type of plaster, which is composed of calcium sulfate hemihydrate, comes as a fine white powder gypsum that stabilizes when soaked with water and allowed to dry for 10 to 15 minutes. Plaster of Paris does not commonly crack or shrink when dry, so it became an exceptional material for casting ceramic molds. In this project, 10 ceramic plaster molds were made to produce sufficient copies of ceramic test pieces.

Experimental Stage 3: Producing Ceramic Copies

For casting copies in the plaster molds, CWE White Earthenware Clay was used, which withstands temperatures of 1080–1160 °C in an electric kiln. According to Pottery Crafts, the producer of the clay, the shrinkage of this clay is 3–5% after drying and 4–6% after firing. The product was supplied in a plastic state, and after the clay dried, it mixed very well with water using a drill mixer to produce a usable consistency of liquid for the slip casting process. Then, all the produced molds were filled with the slip to make as many copies as possible of the ceramic pieces. All the pieces extracted from the molds were fired up to 1000 °C for bisque firing.

Conclusion: The Advantages of Using TPU in Art Production

The table below shows the most significant advantages that ceramists can experience by using TPU printing for plaster mold casting:

Advantage	Description
Time management in industrial and educational environments in case of using TPU	The material composition of TPU allows it to be used for unlimited copies of plaster molds if the TPU mother mold is used for industrial purposes. It can also be used for artistic purposes if the artists request multiple copies. As plaster mother molds can only be used for limited copies of plaster molds, TPU mother molds are an excellent choice for ceramics industries.
Accuracy (keeping details of the design)	The plaster molds extracted from the TPU mother molds were very accurate, and all details appeared to be outstandingly clear.
Meeting customized design specifications requested by end-users of ceramic products	For any ceramic artistic projects, the TPU mother molds can play an outstanding role in meeting the customers' requirements, especially if high quantities of pieces are requested or pieces are occasionally requested according to customers' desires.
Avoiding plaster mother mold defects	The use of the TPU mother molds increased the quality of the final products, and laboratory tests showed that no defects appeared on ceramic molds or ceramic pieces extracted from these molds.

Table 2: Advantages of using TPU printing molds for ceramics industries

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