Proc. of the 9th Intl. Conf. of Asian Society for Precision Engg. and Nanotechnology (ASPEN 2022)
15–18 November 2022, Singapore. Edited by Nai Mui Ling Sharon and A. Senthil Kumar
doi://10.3850/978-981-18-6021-8_OR-01-0250

Binder Jet 3D Printing of Complex Porous Molds for Thermoforming

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KEYWORDS: Additive Manufacturing, Binder Jet Printing, Porous Mold, Thermoforming

Thermoforming involves heating a plastic sheet until it is soft and/or malleable, followed by stretching the plastic sheet against a single-sided mold; the cooled plastic sheet retains the shape of the mold. A main requirement for a quality product is that air must be extracted rapidly and efficiently from between the plastic sheet and the mold surface. Traditionally, this is accomplished with additional features in the non-porous mold, such as drilling vent holes or machining vacuum channels; such features will cause significant markings on the product, especially for thin plastic sheets. Fabrication of porous molds minimizes such issues. With the advent of binder jet 3D printing (BJP), which allows for the fabrication of porous parts with open-cell porous structures via pores-by-processing, novel designs and processes for fabricating porous molds are available. This paper aims to showcase the capability of BJP for porous tooling, including the flexibility to incorporate complex designs.

1. Introduction

In general, thermoforming involves the forming or stretching of a pre-heated thermoplastic sheet onto a single-sided mold [1]. When a vacuum provides the negative pressure to rapidly evacuate gas, the thermoplastic sheet is "forced" against the surface of the mold; this process is also called vacuum forming or vacuum thermoforming. Upon cooling, the thermoplastic sheet retains the shape of the mold, forming the desired product.

Consequently, for quality products, thermoforming molds must be designed such that there are pathways for gas to be rapidly and efficiently evacuated away. Traditionally, this has been achieved via machining venting/vacuum holes [1] into a non-porous mold. However, if these holes are too large, there is a risk of the formation of residual marks on the formed part. The venting holes' diameter is dependent on the material used, including the thickness of the sheet. In general, materials such as HIPS, ABS, PC, and PMMA, require holes of diameter < 0.8 mm during vacuum forming, while materials such as PP require holes of diameter < 0.3 mm [2].

With porous molds, the aforementioned surface defects/marks can be eliminated. Moreover, porous molds provide the benefit of even evacuation of gas over the whole mold surface, providing opportunities for forming precise parts without the aid of a plug assist to spread the sheet out more evenly during thermoforming.

Commercially, porous materials, such as METAPOR® and ALUPOR™, are being utilized to fabricate porous tools, including porous molds. However, fabrication of molds using such materials generally involves subtractive manufacturing or traditional casting techniques; the shapes of the porous tools fabricated are still limited.

With the advent of binder jet 3D printing (BJP), the fabrication of porous tools and parts with open-cell porous structures are achieved via pores-by-processing, whereby the powders held together by the binder are sintered together to a certain degree, while still obtaining an open porous microstructure [3]. Importantly, with BJP, comes the ability to manufacture various complex geometries that are not achievable or difficult to achieve via traditional methods, or even Computed Numerical Control (CNC) milling. This paper aims to showcase one useful application of BJP fabricated parts: porous molds for thermoforming purposes.

2. Binder Jet 3D Printing of Porous Molds for Thermoforming

2.1 BJP Fabrication and Design of Complex Porous Molds

This study's BJP fabrication of complex porous molds was accomplished via a feedstock consisting of new and recycled stainless steel grade 316L (SS316L) gas-atomized powders (20–53 µm) from Höganäs. The molds were printed using the ExOne MFlex 3D Printer with the ExOne proprietary aqueous binder; binder saturation of 60% and layer thickness of 100 µm were utilized. The printed green parts were cured at 200 ºC before depowdering. Subsequently, the parts were debinded and sintered using the Solar Manufacturing vacuum furnace at temperatures up to 1250 ºC, under high vacuum, and at a partial pressure of Ar. The open porosity of the SS316L porous parts fabricated in this manner is about 39%, as measured by the Archimedes method.

This paper aims to showcase the capability of BJP for porous tooling, including the flexibility to incorporate complex designs. As such, different types of molds will be discussed; the molds are described in Table 1 and the *Holes Mold (Porous)* is illustrated in Figure 1. The molds described in this study are approximately 200 mm by 200 mm in size and 10 mm to 30 mm in height.

Table 1 Types of Molds (In this study)

Mold	Description
Holes Mold (Porous)	BJP fabricated female porous mold for benchmarking purposes; holes with diameters ranging from approximately 5–20 mm, and depths of 10, 20, and 25 mm.
Holes Mold (Non-Porous)	A non-porous version of the above-mentioned female mold fabricated via CNC milling. Vent holes have been included in some of the holes.
Logo & QR Code Mold (Porous)	BJP fabricated mold with further complex shapes and designs.

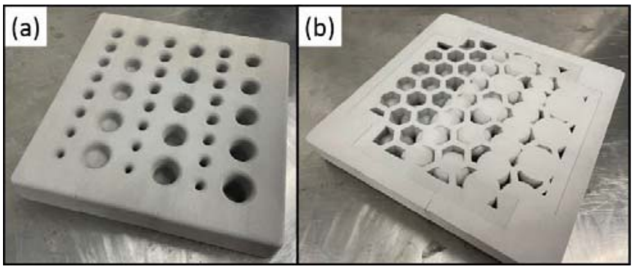

Fig. 1 Illustration of BJP-fabricated *Holes Mold (Porous)* (a) from the top (thermoforming surface), and (b) from the bottom/underside.

Both the *Holes Mold (Porous)* and *Holes Mold (Non-Porous)* were designed such that there was a range of holes with diameters ranging from 5 mm to 20 mm. Furthermore, there are three sets of holes on each mold, with depths of 10 mm, 20 mm, and 25 mm, from left to right respectively (Figure 1a). Vent holes of 1 mm in diameter were drilled into some of the holes in the *Holes Mold (Non-Porous)*, in order to evaluate both performances, with and without the vent holes.

A honeycomb design was incorporated into the underside of the BJP-fabricated porous molds (eg. Figure 1b), to reduce the material wastage as well as to better facilitate the rapid evacuation of gas during thermoforming. The strength of the porous mold with such a honeycomb design on the underside has been assessed to be capable of continuing its function as a thermoforming mold; the fatigue life assessment is beyond the scope of this study.

2.2 Thermoforming Capabilities of Binder Jet Printed Porous Molds

The material used for thermoforming is a 1 mm thick polycarbonate sheet from Sabic Innovative Plastics™ (Lexan F6000 Sheet). This sheet is a commercially used thermoforming material that is flame retardant. The thermoforming process was carried out via the Formech HD1500 fully automatic vacuum former, with the mold being pre-heated to 90ºC before thermoforming at 215 ºC; the sheet was pre-dried at 120ºC for 3 hours beforehand.

The main analysis of this study is based on the performance of the *Holes Mold (Porous)* versus the *Holes Mold (Non-Porous)* in thermoforming capabilities. Figure 2 illustrates the thermoformed products from the two molds.

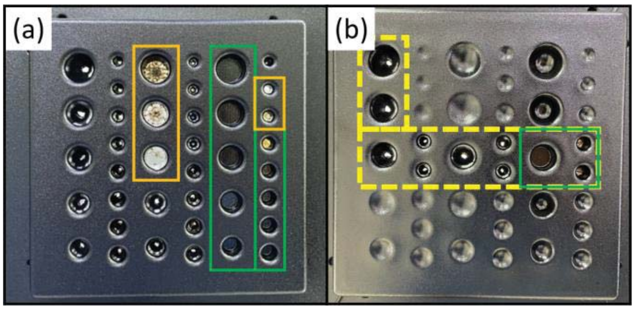

Fig. 2 Thermoformed product using the (a) *Holes Mold (Porous)* and using the (b) *Holes Mold (Non-Porous)*. The yellow dashed lines in (b) illustrate the holes that had vent holes drilled into the *Holes Mold (Non-Porous)*.

Overall, the *Holes Mold (Porous)* was able to properly evacuate gas from all the holes. This can be seen from the sheet material being drawn into the depth of the holes. However, due to the thickness of the sheet used (1 mm), as well as the material itself, there was insufficient material to be drawn to fully cover the holes that require a large draw ratio (depth of the aperture divided by the length of the shortest cross-section). As a result, in terms of features that were properly formed, the *Holes Mold (Porous)* was able to form most of the holes (diameters from 20 mm to 6 mm) with 10 mm depth (green region in Figure 2a); the *Holes Mold (Porous)* was also capable of forming the larger holes (diameters from 20 mm to 16 mm) that required a larger draw ratio with a depth of 20 mm. Nevertheless, it should be reiterated that the main aim of this study is to showcase the ability of the BJP fabricated *Holes Mold (Porous)* being able to properly evacuate gas from all the features on the mold.

In comparison, it is obvious from Figure 2b that features on the *Holes Mold (Non-Porous)* cannot be properly and precisely formed if there are no vent holes drilled in the holes; the yellow dashed region shows the holes that had vent holes drilled into the *Holes Mold (Non-Porous)*. Furthermore, from the regions that had vent holes, the *Holes Mold (Non-Porous)* was only able to properly form features in three holes (green region in Figure 2b). For the *Holes Mold (Porous)*, it could form features in four holes in the same region (Figure 2a). The ability of the *Holes Mold (Non-Porous)* to form the additional hole (in the middle of the mold) could be related to its ability to encourage even evacuation of the gas out from between the sheet and the mold. This is firstly assisted by the mold being porous, and secondly, the design on the underside (Figure 1b), which encourages an approximate even amount of porous material over each feature, even if the depths of the features are different.

Lastly, while the presence of vent holes allowed for gas evacuation in the *Holes Mold (Non-Porous)*, this was accompanied by the disadvantage of defects forming, namely visible nipples on the formed parts (Figure 3). The significance of this drawback will be dependent on the application of the final product. For products that require high precision of contour definition or sensitive visible surfaces, the presence of nipples on the formed part will be detrimental.

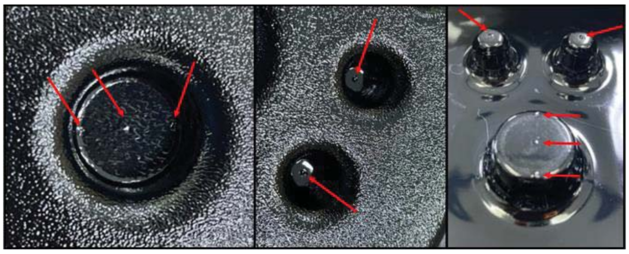

Fig. 3 Nipples on the formed features, indicated by the red arrows, due to the vent holes on the *Holes Mold (Non-Porous)*.

3. Conclusions and Final Remarks

Overall, Table 2 describes the main findings of this study, in terms of benchmarking the thermoforming capabilities between the *Holes Mold (Porous)* and *Holes Mold (Non-Porous)*. The key takeaway is that BJP fabricated porous molds do hold the potential and capability to function as porous tooling, bringing with it the technology to manufacture complex designs that cannot be easily fabricated traditionally, or where vent holes cannot be easily included.

Table 2 Main Comparison of Thermoforming Capabilities between *Holes Mold (Porous)* and *Holes Mold (Non-Porous)* (In this study)

Thermoforming Capabilities	*Holes Mold (Porous)*	*Holes Mold (Non-Porous)*
Gas Evacuation	Gas was able to be evacuated from all features (holes).	Gas could only be evacuated when vent holes are present
Forming Features	Able to form most holes at 10 mm depth. Able to form the larger holes at 20 mm depth, including ones that failed on the *Holes Mold (Non-Porous)*.	Unable to form features if no vent holes are present. Nipples present on formed holes due to the presence of vent holes.

One such example of the complex design is illustrated via the *Logo & QR Code Mold (Porous)* in Figure 4. Figure 4a showcases the ability of BJP to fabricate intricate features, such as the QR code; the subsequent successful forming of such features is shown in Figure 4b. If such a mold was to be fabricated via traditional methods, using non-porous materials, there would first be issues in finding appropriate non-critical positions to machine vent holes, then there would also be issues in machining vent holes small enough to not be visible on the formed product.

Nevertheless, it must be mentioned that the BJP fabricated molds used in this study were utilized as received after sintering. Therefore, the surface finishing, as with most BJP fabricated parts, is not smooth. This drawback is not an issue in the current study, in part due to the matte finishing of the sheet used. However, there can be applications where surface finishing is critical, in terms of formed product surfaces, as well as the ease of demolding during the thermoforming process.

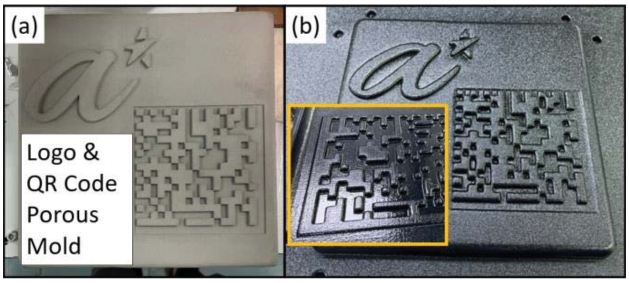

Fig. 4 The *Logo & QR Code Mold (Porous)* is shown in (a). (b) illustrates the formed part using the mold in (a); the inset reveals the underside of the formed QR code feature.

ACKNOWLEDGEMENT

The authors would like to acknowledge the financial support of Industry Alignment Fund – Industry Collaboration Projects (IAF-ICP) Grant No. I1901E0042.

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