Rapid tooling development for low volume injection molding of cosmetic compacts

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Abstract. This study aimed to explore the capability of different additive manufacturing (AM) or 3D printing technologies to rapidly manufacture mold inserts for injection molding as well as to evaluate the performance of the printed mold inserts and the quality of the injection molded parts. Fused filament fabrication (FFF), stereolithography (SLA), and multi-jet fusion (MJF) 3D printing technologies were used to produce the mold inserts, whereas a cosmetic compact base was selected as the case study part. The results obtained show that it is possible to use the mentioned technologies to manufacture tool inserts for rapid prototyping or low volume production of cosmetic compact bases using injection molding. When using the FFF mold inserts, the cosmetic compact bases produced were not of the best quality and surface finish but still acceptable for prototyping purposes only. The vertically printed SLA mold inserts as well as the MJF mold inserts produced cosmetic compact bases with no flashes and the best surface finish. The MJF mold inserts had excellent thermal properties so that apart from HDPE, a higher melting temperature ABS was also successfully molded. Also using the MJF mold inserts, the highest production number of 80 cosmetic compact bases of a good quality could be achieved.

Introduction

Rapid Tooling (RT) is a rapid production of tools or molds using additive manufacturing (AM) also as known as 3D printing technology, which were introduced a couple of decades ago [1]. Additive manufacturing is a layer-by-layer process using only one machine, which is capable of joining materials to manufacture a desired three-dimensional object. This technology is the opposite of traditional manufacturing, where an object is carved by removing the unwanted extra material [2]. In other words, rapid tooling is the use of AM technologies to produce tools, molds, or dyes, in order to produce parts using a subsequent manufacturing technique such as injection molding to produce parts or prototypes instead of using an AM technology directly, which may take longer and cost more if a certain quantity is required [3-5]. Although the process and technology used for rapid tooling is the same as the ones used in AM, the purpose is different. Using rapidly and additively manufactured tools/molds, the final products or prototypes are expected to be better since the parts can be molded from the desired molding material and fully dense.

RT could save time and money in the injection molding industry since the designer can analyze the performance of the AM tool and confirm that the tool has met its objectives before starting the long and expensive process of manufacturing the conventional tool steel mold. This will save a company months of work and tens of thousands of euros [6,7]. On the other hand, if a rapid tool will be used for the actual production of finished parts and not only to produce several prototypes to test the tool and its expectations, then surface finish will also be an issue and a very good quality product is expected [8]. In rapid manufacturing/rapid prototyping process, surface finish is not that of an issue since these technologies have a free form nature [1].

RT can be divided in two categories, namely direct and indirect tooling. These two categories are further divided into other two categories which are soft tooling and hard tooling [10]. Hard tooling is used when high production runs are required. Normally for hard tooling tool, steels are applied using metal AM technologies such as, laser beam powder bed fusion process (LB-PBF). On the contrary, soft tooling is mostly used for a few runs. Therefore, this process could make use of thermoplastic materials, epoxy resins, and low melting temperature metallic alloys using AM technologies such as fused filament fabrication (FFF) and stereolithography apparatus (SLA).

This study aimed to explore the capability of different AM or 3D printing technologies to rapidly manufacture soft tools for injection molding as well as to evaluate the performance of the 3D printed soft tools and the quality of the injection molded parts.

Materials and Methods

Case Study Part.

A small Terra cosmetic compact of Toly Product Ltd. Malta was selected as the case study which consists of a lid and base. For this study, only the base was considered, as can be seen in Fig. 1, which is mass produced from a mixture of acrylonitrile butadiene styrene (ABS) and styrene acrylonitrile (SAN) polymers. The injection mold used in the actual mass production process had two sliders, one at the front and another at the back. The back section has sliding cores to form holes on each side of the cosmetic base to accommodate two metal pins, which are used as a hinge to allow the user to open and close the lid of the cosmetic compact. At the front side of the base, a protruded bump is formed using another slider which is used as a snap-fit join to lock or release the lid, Fig. 1a. The part was injected from the center on the bottom side, using a 2-cavity hot runner mold. The injection point can be easily observed on the center bottom of the original part, while the four ejector pins are located in the well sections of the part, as can be seen in Fig. 1b.

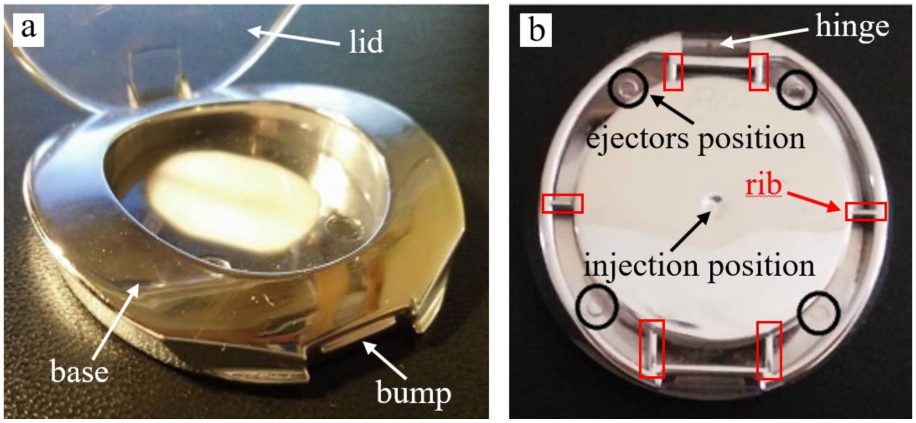

Fig. 1. Small Terra cosmetic compact top view (a) and its base's bottom view (b).

Part Design Simplification.

The design of the cosmetic base required slight simplifications so that the cosmetic bases could be produced without the above-mentioned sliders using a cold runner mold instead of the hot runner mold as in the actual mass production. The holes for the hinge metal pins and the snap-fit bump to lock the lid both of which are formed by the sliders were eliminated. On the bottom side, the base had six ribs in its recess to give the part extra rigidity and strength. Two of these ribs, one on each side, were eliminated to decrease part complexity and also at the same time to give space for ejector pins. The remaining four ribs which are close to the hinge and snap-fit areas are slightly thickened since they were considered to be weak so that it was not ideal for the tooling/mold inserts which are to be manufactured using additive manufacturing. The last necessary simplification was to alter the parting line, which also determines the design of the core and cavity inserts as well as the position of the gate, as can be seen in Fig. 2.

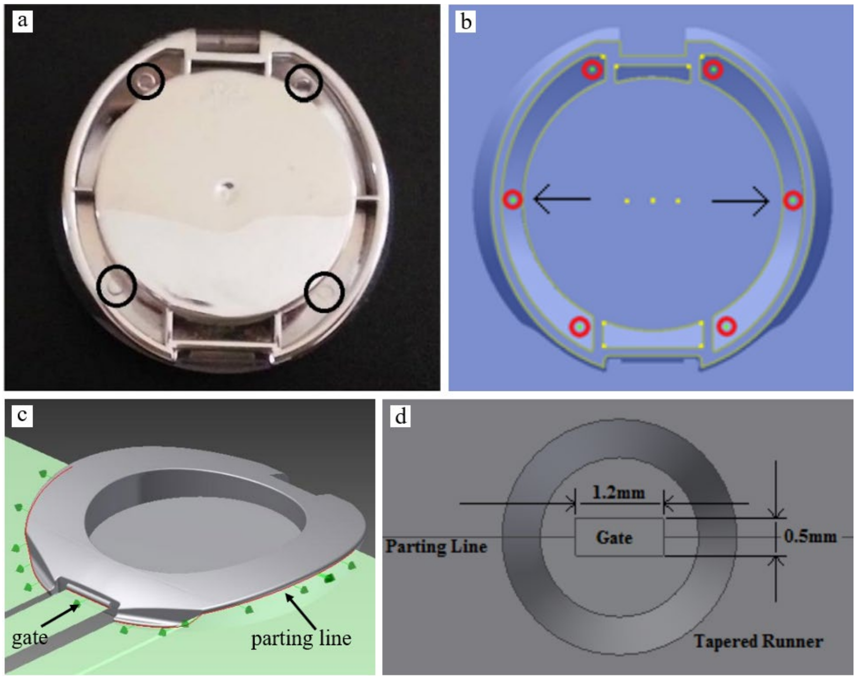

Fig. 2. Ejector pins position on old (a) and new (b) part design; new parting line and gate position (c,d).

Mold Design and Manufacture.

The mold designed for this study was a 2-plate, 2-cavity cold runner mold, without sliders as previously explained. The mold design started from a complete mold base including the mounting and cavity plates, locating ring, riser/spacer block, the locating sleeves, ejector pins, ejector retainer plate and support plate, etc. The cavity plates from both injection and ejection sides have a pocket for a metal insert on which two pockets on each side were machined to accommodate the 3D printed or additively manufactured (AM) mold inserts, as shown in Fig. 3.

Other mold components or features such as runner system, gate type and size, ejection forces including the number and position of the ejector pins, cooling time including the cooling channels were calculated or designed according to guidelines given in Kazmer [11] and Menges et al. [12], although they are for conventional mold design. However, since the aim of this study is not to achieve high production rates and the shortest of cooling or cycle time as well as the printed mold inserts are manufactured from polymer materials with a low heat conductivity, these calculations were not given a great deal of importance. They serve mainly as starting points of the mold design and to ensure that the deviation in the injection molding process including the molding results comes from the 3D printed mold inserts.

In deciding the gate type, the type of runner system, the desired method of de-gating, the allowable level of shear rates through the gate, the resulting flow that is desired as well as the material used in injection molding were all considered. A tab gate is usually used for a simple cold runner type characterized with a manual de-gating, moderate melt shear rates and radial flow. These characteristics were all desirable for this study, and thus, a tab gate, with dimensions as shown in Fig. 2, was designed. The shear rates and the pressure drop at the gate as well as the gate freeze time were also calculated according to Kazmer [11].

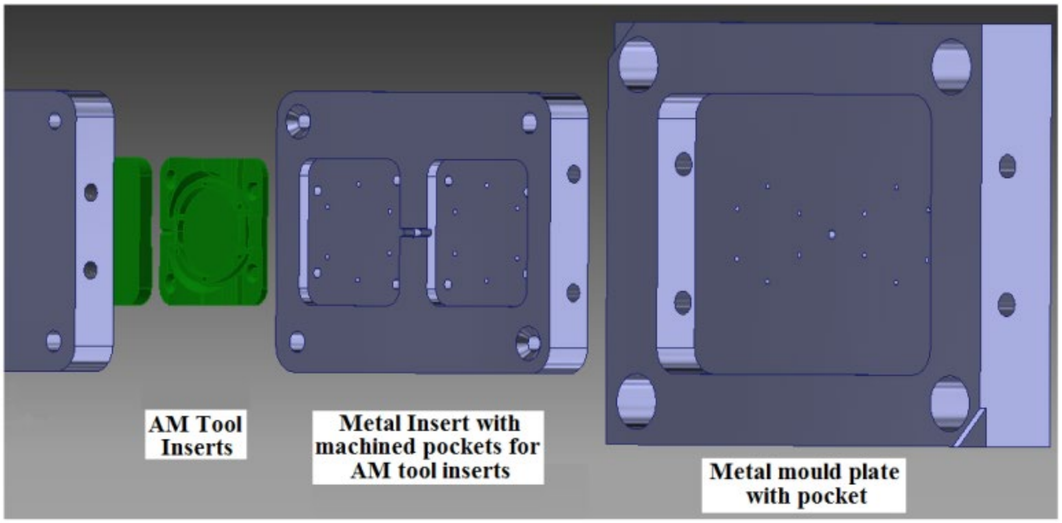

Fig. 3. Metal mold plate, metal insert, and 3D printed (AM) mold insert of the ejection side.

Although the cooling system and its efficiency is of great importance, it was kept simple not to compromise and complicate the machining of the channels. The cooling channels layout in the metal inserts can be seen in Fig. 4. Each cavity had its own U-shaped cooling line. The cooling channels were 46 mm apart on the ejection side and just 27 mm apart on the injection side as shown in Fig. 4a-b. On the ejection side, the cooling channels could not have been machined closer due to the ejector pin holes, while on the injection side there are no such restrictions, the cooling lines were made closer for increased efficiency, higher cooling and thermal dissipation rates. The flow direction of the coolant with a temperature of 19˚C, is indicated by the arrows in both Fig. 4a-b.

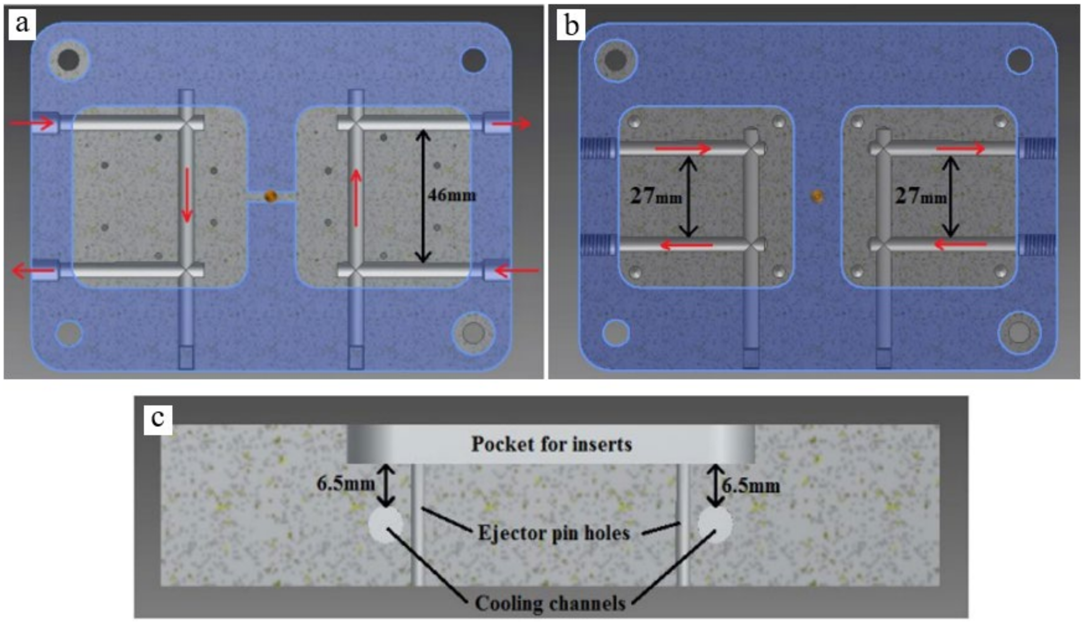

Fig. 4. Cooling channel layout on ejection (a) and injection side (b) of the mold as well as the cross-sectional view of ejection side (c).

In this study, three polymer additive manufacturing or 3D printing technologies were used to print the mold inserts, namely fused filament fabrication (FFF), stereolithography (SLA), and multi-jet fusion (MJF). Two desktop FFF 3D printers (Up Plus 2 and Zortrax M200) were used to manufacture the mold inserts using acrylonitrile butadiene styrene (ABS). ABS was selected based on its overall good properties for mold inserts such as good heat resistance, relatively high heat deflection temperatures, hardness, and toughness. For SLA technology, the mold inserts were printed with Formlabs Form 1+ printer using its standard resin and with Viper Si2 printer using its Accura Xtreme resin. Regarding the MJF technology, ProJet 3500 together with VisiJet M3-X material was used to build the mold inserts.

Fig. 5 shows an example for a mold insert that was manufactured using the FFF 3D printer Zortrax M200 before and after the removal of support material, and Fig. 6a shows another example for SLA mold inserts manufactured using Viper Si2. Fig. 6b and Fig. 6c show the final mold setup from the ejection and injection side which has two pockets and, on each of which, 3D printed mold inserts can be mounted, in this case two different FFF mold inserts 3D printed using UP Plus 2 printer.

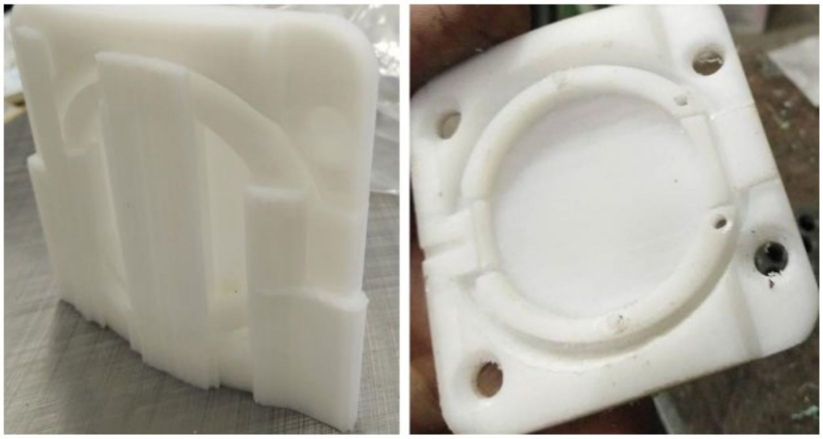

Fig. 5. An example for mold inserts FFF 3D printed on the Zortrax M200 before and after the removal of support material.

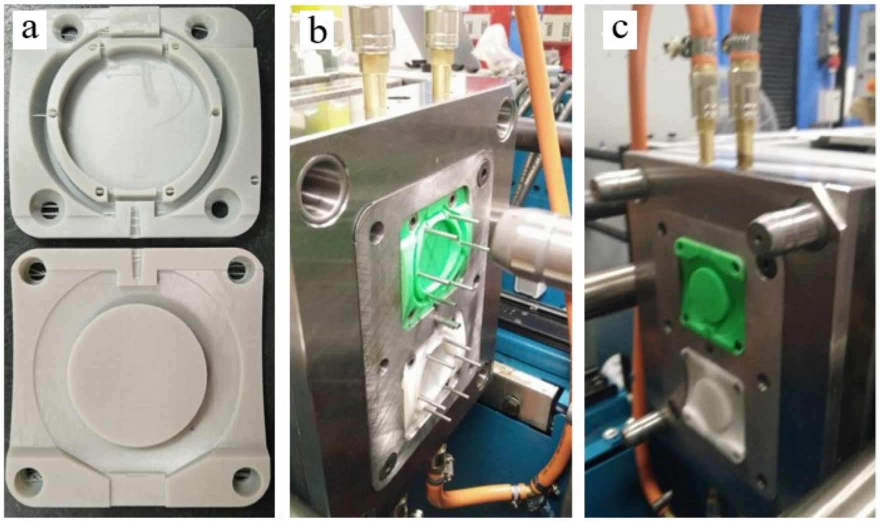

Fig. 6. SLA 3D mold inserts manufactured using Viper Si2 (a), ejection side (b) and injection side (c) of the 2-cavity mold with two different FFF mold inserts 3D printed using UP Plus 2.

Injection Molding Experiments.

The experiments were carried out on Boy 22E injection molding machine. Considering the fact that the mold inserts are printed from polymer materials, the selection of the molding materials was based mainly on a low processing temperature range. For the main injection molding experiments, high density polyethylene, HDPE HMA 016 from ExxonMobil Chemical, was used to produce the cosmetic compacts with the main processing parameters as shown in Table 1. Apart from HDPE, molding experiments using acrylonitrile butadiene styrene (ABS) were conducted to test the mold inserts printed using high temperature materials.

Table 1. Injection molding parameters for HDPE.

Temperature		**Injection**			**Holding**		**Cooling**
Melt	**Mold**	**Pressure**	**Speed**	**Time**	**Pressure**	**Time**	**Time**
165°C	19°C	800 bar	15 cm^3/s	1.5 sec	342 bar	3.5 sec	35 sec

Results

Mold Inserts Temperature and Cooling Time.

Using an infrared camera, the temperature of the mold inserts as well as the parts upon mold opening can be observed as can be seen in Fig. 7 (left). The temperature of the parts and the cavity of the mold inserts was around 100˚C. Thus, after ejection of the part, further cooling of the mold inserts is required before closing them again to start a new molding cycle. In the case of Zortax mold inserts, further cooling time (open mold) of 240 s was required, which resulted in a total cycle time of 280 seconds including the injection time, the holding time, cooling time (with the mold closed) and the further cooling time with the mold open. Although the temperature of the mold inserts increased after each molding cycle, the desired mold temperature could be reached approximately at the same time as can be seen in Fig. 7 (right).

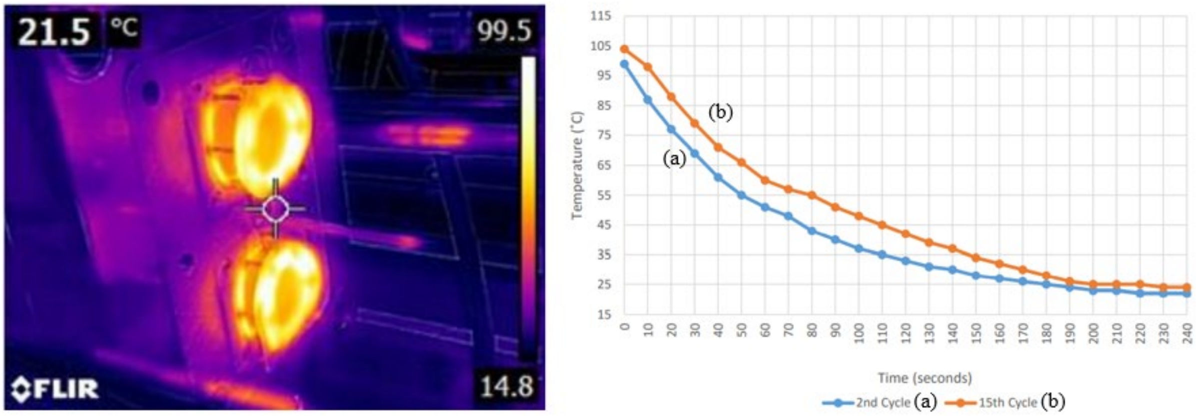

Fig. 7. IR thermal image of part (left) and parts' temperature decrease during further cooling after the mold is opened (right).

Evaluation of Molding Process and Molded Parts Quality.

Using the FFF printed mold inserts, several molding problems occurred especially during demolding e.g. puncturing of the parts by the ejector pins as the parts tended to stick onto the cavity surface of the mold inserts due to the relatively rough surface of the mold inserts as well as some flashes formed on the molded parts. This was solved by further decreasing the part temperature before demolding, the application of mold release agent, and the reduction of the ejection speed. Even though the mold inserts were printed with 100% infill, certain areas had voids, which collapsed slightly inwards during the first molding cycles. This was replicated on the molded parts. Overall, the cosmetic compacts were not of the best quality and surface finish but they are acceptable to produce prototypes with molding quality and from the desired molding material.

In contrast to the desktop FFF printed mold inserts, the quality and surface finish of the mold inserts printed with SLA Viper Si2 using Accura Extreme were excellent. However, the inserts printed horizontally showed steps on the top curved surfaces of the mold inserts which were replicated on the molded parts and also caused a formation of small and thin flashes, as shown in Fig. 8.

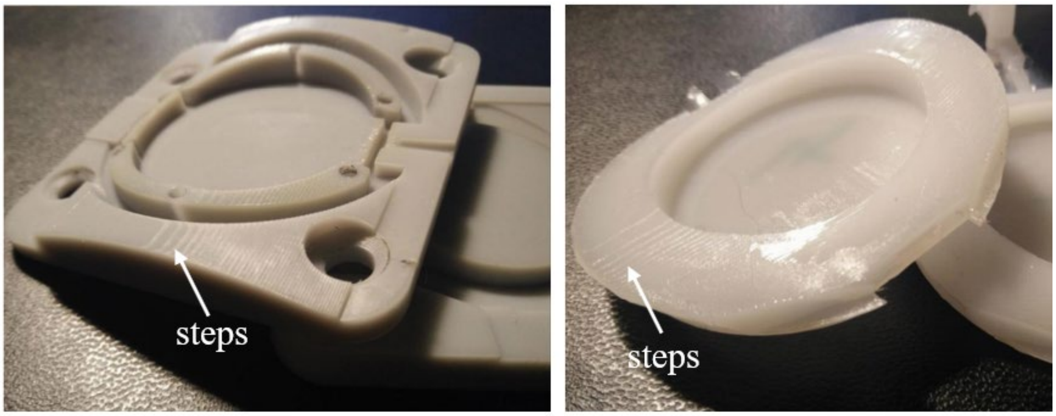

Fig. 8. Viper Si2 SLA horizontally printed inserts using Accua Extreme (left) and the molded cosmetic compact base (right).

The problems related to the above step and flash formation was eliminated by printing the mold inserts vertically. A finer surface finish of the curved sections of the mold inserts could also be achieved. This resulted in very few flashes only after the 15th molding cycle, while all front features of the molded parts were clearly replicated. A total of 27 molding cycles were carried out with a relatively good quality of the produced cosmetic compact bases, as can be seen in Fig. 9a.

Similar to FFF mold inserts, the tab gates of the SLA mold inserts lasted only a couple of molding cycles before breaking off. However, the strength and hardness of these SLA inserts were better compared to the FFF inserts. The rest of the mold features sustained the heat and pressure from the injected melt. The protruding sections of the mold inserts including the core on the injections side turned brownish in color as can be observed in Fig. 9b.

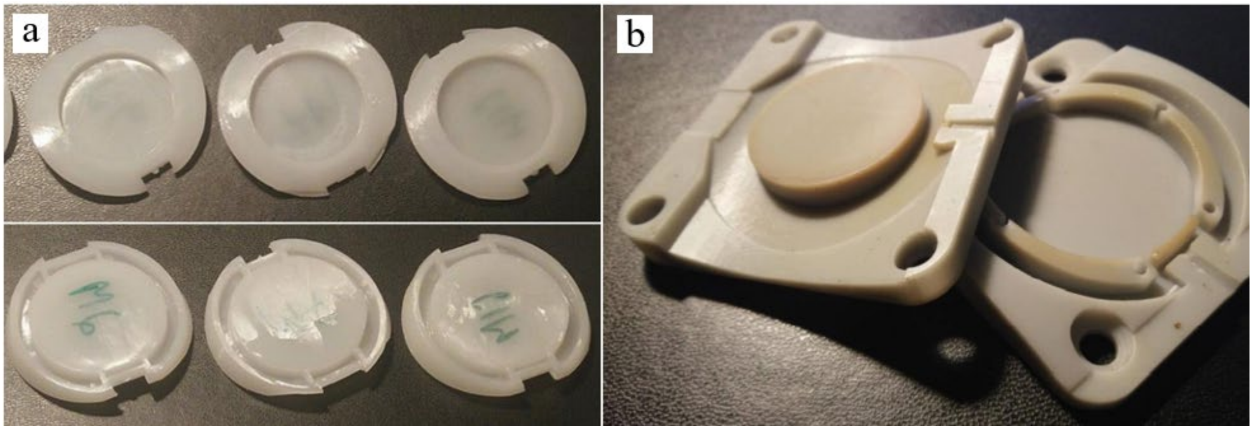

Fig. 9. Molded cosmetic compact bases (left) and used SLA mold inserts vertically printed using Viper Si2 and Accua Extreme resin (right).

The MJF mold inserts manufactured on a PolyJet 3500 printer using VisiJet M3-X material had excellent thermal properties. These inserts should be capable of withstanding temperatures up to 350˚C after annealing. Therefore, apart from molding using HDPE, ABS, which has a much higher processing temperature of around 200˚C, was also successfully used to mold a few parts at the end of the experiments using these mold inserts. No part puncturing occurred in the entire molding experiments and no flashes were formed up to the first 22 molding cycles. The parts produced show the best surface finish compared to ones molded using other mold inserts, Fig. 10.

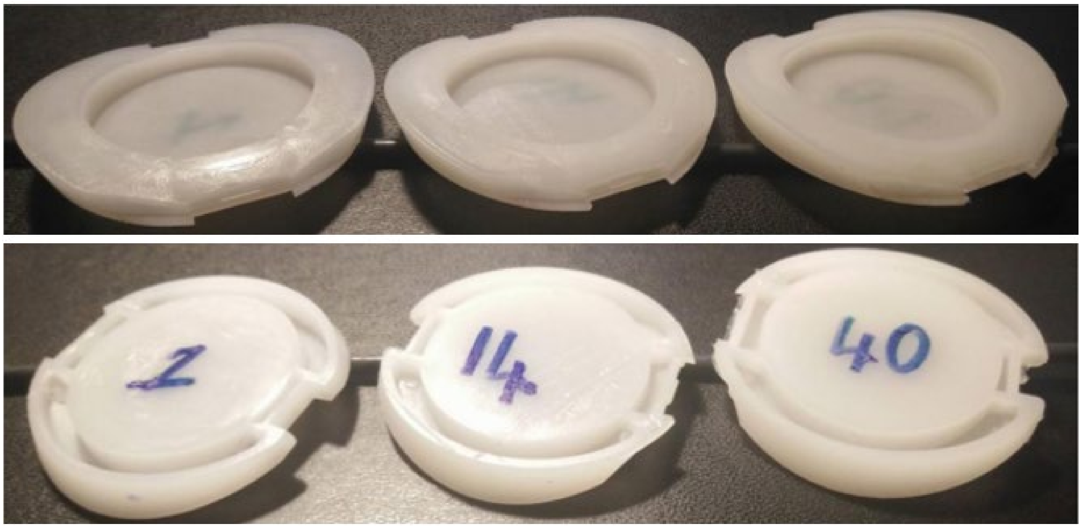

Fig. 10. Cosmetic compact bases top and bottom view molded using MJF mold inserts.

Fig. 11. MJF mold inserts with cracks after 40 molding cycles using HDPE and other 6 successful molding cycles using ABS as the molding material.

The MJF inserts performed excellently and, in contrast to other mold inserts additively manufactured using FFF and SLA 3D printers, the gate of the MJF mold inserts was not broken. The only drawback was that these inserts were discovered to be quite brittle and after a considerable amount of number of cycles, they cracked as shown in Fig. 11. These cracks initiated from weak areas such as the mounting holes. Other points of crack initiation were the ejector pin holes. These cracks kept propagating and getting bigger in size and depth, and after 40 molding cycles using HDPE and other 6 successful molding cycles using ABS. Despite the cracks, parts could be still injected but slight flashes were formed through the cracks formed.

Summary

Although there were some molding problems in the first runs when using the FFF mold inserts and the cosmetic compact bases produced were not of the best quality and surface finish, these could be substantially improved in the next runs. When using the vertically printed SLA mold inserts as well as the MJF mold inserts, the results obtained were excellent since no flashes were formed in the first few molding cycles and a good surface finish was also achieved. The MJF mold inserts had very good thermal properties so that apart from HDPE, ABS was also successfully molded which is the main material for the actual mass production of the cosmetic compact bases. The SLA inserts were considerably less thermal resistant, but a total of 27 molding cycles were easily accomplished producing 54 good cosmetic compact bases. The maximum production number of 80 cosmetic compact bases could be achieved using the MJF mold inserts. This proved that, using advanced materials available today, some of the AM technologies which are normally used for rapid prototyping, rapid manufacturing, and soft indirect rapid tooling applications, can also, easily be used, in hard direct tooling. This saves time and resources, which could give companies a competitive advantage, since development and manufacturing time are substantially reduced.

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