CONFIDENTIAL

RAPID TOOLING

Additive manufacturing of blow molds for rapid prototyping of cosmetic bottles

Abstract

Prototyping is one of the most costly and time consuming processes in developing novel packaging ideas and concepts. Rapid prototyping of cosmetic bottles via 3D printing of prototype blow molds is investigated. The lead time of new prototypes needs to be reduced to a time span of 5-7 days while maintaining or preferably reducing prototype cost. Different 3D printing methods and materials are considered. Currently, the most widely applied process is the polyjet machine using green digital ABS provided by stratasys. It is shown that this process and material might be more expensive and time consuming than DLP or CLIP with a cheaper and less qualitative material. A concept for a mold design is developed. There are two options. One is to use standard steel frame containing cooling channels and fixation points in which only a printed bottle form is printed. The other is to print the entire mold and only use steel plates to fix the mold in the blow molding machine. Currently, printing the entire frame seems to be more advantageous because it can be used in any blow molding machine.

21 September 2017

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1. PROJECT DESCRIPTION

Packaging development has changed over the last decades. The importance of developing new shapes and technologies lies not only in the functionality but also and maybe more importantly in the branding opportunities for the product. Packaging is the first thing the customer sees in the store. It is important to be different and stand out from the competition. Rapid development of new ideas is vital to keeping the products position in the market.

Containers for cosmetic applications exist in all different shapes and sizes. New ideas are being developed at significant speed. For example, the development of lower weight packaging is useful for saving material and transportation cost. Also, better touch and squeeze ability can often be achieved with thinner bottle walls. All of these new requirements need to be designed to be in balance with good function and processability of the packaging (e.g. thinner walls can lead to failure of the packaging in storage or drop testing and also lead to problems during filling).

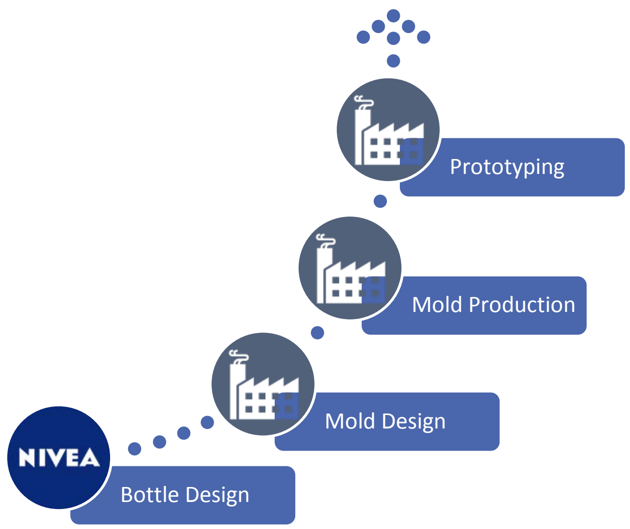


Figure 1 - Current prototyping process. Mold design/production and prototyping are done by one specific supplier. Time determining step: Availability of blow molding capacity.

When new ideas arise, prototypes need to be produced and tested on their function and processability. The prototyping process can be very time consuming as well as costly. For bottle production, this means the production of prototype blow molds. These blow molds are delivered to the manufacturer who produces a small volume of prototypes by extrusion blow molding a PP-, PE- or PET-material. The prototype molds are usually cast in steel or cut in aluminum.

While the option of cutting the molds out of aluminum can be done within 1-2 weeks, it is still quite expensive and often too time consuming. Being faster than the competition is key. This is why the technique of additively manufacturing (i.e. 3D printing) prototype molds was developed. Suppliers claim that 3D printing the molds can reduce lead time by up to 75% and reduce tooling cost by up to 60% [1, 2].

Another advantage with this way of working is the flexibility. A mold is designed and produced in-house and is sent to any available bottle supplier for prototyping (see Figure 2). This eliminates the dependence on the suppliers' available production capacity. With the current prototyping process (see Figure 1), the time determining step is the capacity at the tooling workshop and blow molding production line(s) at the supplier. Currently, only the bottle design and sometimes also the mold design is made in-house by computer aided design (CAD) software. The 3D data are shared with the supplier who designs the mold, produces it and waits until one of his blow molding machines is available until he can produce and deliver prototypes.

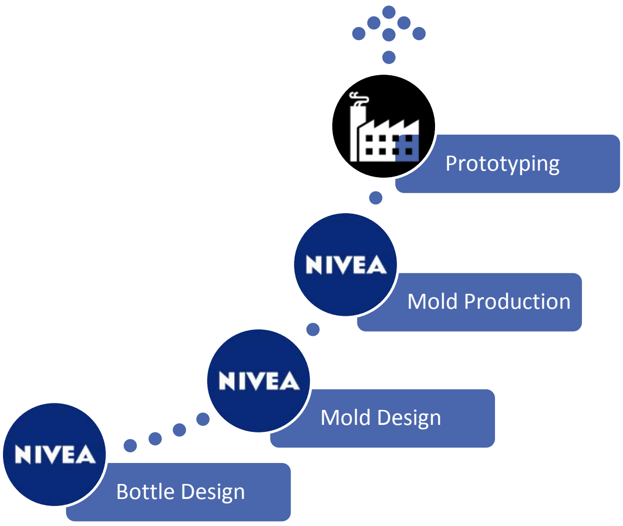


Figure 2 - Rapid prototyping. Bottle design, mold design and production are done in-house. The prototyping (blow molding) can be done at any available blow molding machine.

Choosing the most convenient 3D-printing technology and correct material of construction (MoC) for these prototype molds proves difficult. While on the one hand the molds need to withstand the operating pressure and temperature during the blow molding process, they need to be produced quickly and cheap. Available options are investigated in chapter 5.

Furthermore, the most flexible mold design that can be used by any supplier needs to be found. It is important to look at the different blow molding machines and their requirements like size, orientation points, fixation points etc. A preliminary design is developed in chapter 4.

2. BACKGROUND

2.1. BLOW MOLDING

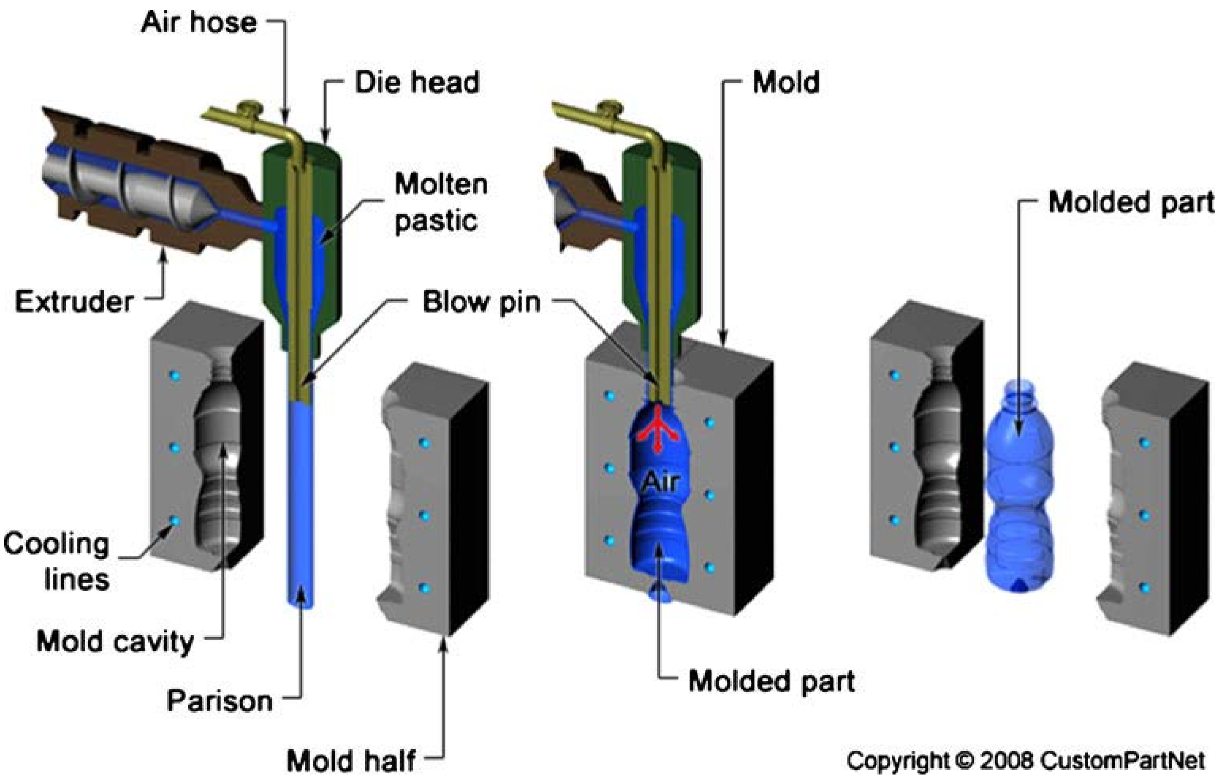


Figure 3 - Blow molding process [3]

Blow molding is a common process used in the packaging industry. Many hollow containers, like bottles, pots or tanks, are produced out of thermoplast materials. In the process, first a polymer melt (also called a parison) is extruded and placed in between two metal mold halves. Next, the mold is closed and the parison is inflated with compressed air under high pressure (see Figure 3). The mold walls are vented and a vacuum may be applied. The parison is molded to the desired shape, is cooled and is subsequently ejected.

The parison can be produced by extrusion (EBM), or by injection (IBM) and stretch blow molding (SBM) then it is called a 'pre-form'. EBM is the most commonly used process and involves extrusion of the polymer into a die. The extruded blow pin or `parison` is transferred to the mold directly and cut at preset time intervals as shown in Figure 3. This can be a continuous or intermittent process. In the intermittent process, the extruder is equipped with an accumulator/head device. Once the desired volume has accumulated a ram or plunger pushes the material rapidly through the head-die assembly. The mold clamp mechanism does not need to transfer to a blowing station. The next parison is only extruded after the part is blown, cooled and removed from the mold [4, 5, 6].

IBM is the process where the parison forms a pre-form which is first injection molded and is supported by a metal core pin. It is subsequently blown into shape and is thus an intermittent process. This process is not often used but is mostly used for bottles with very precise wall thickness and high quality bottle-neck finish and/or made of polymers that cannot be processed with EBM. In the SBM process the heated parison from either EBM or IBM is inflated. The parison can be stretched by an internal stretch rod or external gripper and is subsequently radically stretched by blown air to form container against the mold. The initial stretching step is used to align the polymer chains and thus improve the mechanical properties of the material. It is only used for crystalline and crystallizable materials such as polypropylene [3].

In this report, EBM is the process in focus because it is the most common process used for bottle production by Beiersdorf. More specifically, a design of a mold for an already existing bottle will be developed. If the rapid tooling process proves to work for this case, further cases may follow.

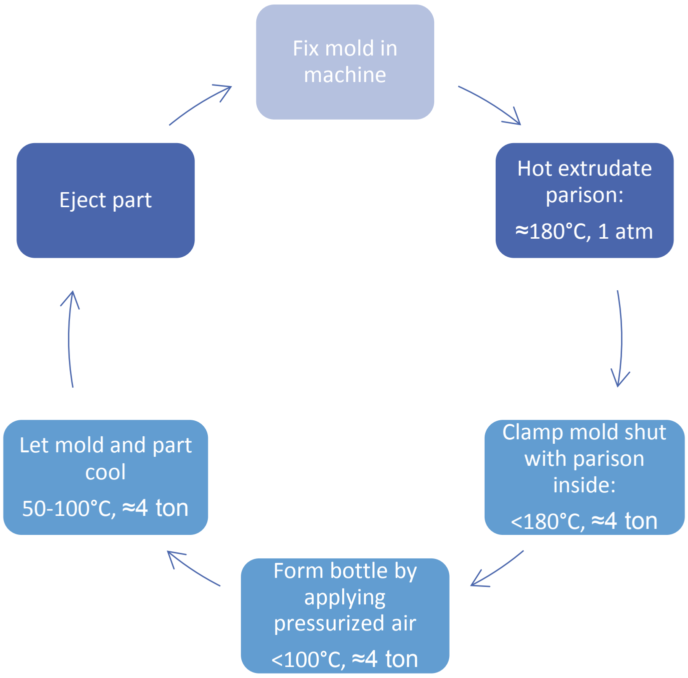


Figure 4 - Blow molding process in stages. Estimated operating conditions provided by suppliers.

Figure 4 shows a simplified overview of the process that a blow molding tool goes through during each cycle. This will be important for the design of the mold as it will determine most material and dimensional requirements. The orange colored steps, are related to the processing conditions on the mold. The blue colored steps, are more related to the material that is being processed, i.e. the polymer used to form the part.

The temperature of the polymer melt will be around 180°C after leaving the extruder as a parison. The polymer melt starts cooling directly after leaving the extruder head. The mold is shut and clamped well by applying pressure of about 3 tons on it. Usually The parison is formed to the mold by blowing with air. The polymer melt touching the mold surface is already much cooler at this point. The mold and part are now left to cool below a temperature that production workers are not burned and the part will not be deformed. This is about 50-60°C.

2.2. RAPID TOOLING

Rapid tooling is not to be confused with rapid prototyping. Rapid prototyping is used as a term of fast production of prototypes like bottles, dispensers, etc. while rapid tooling describes the faster testing of tools like blow molds, injection molds, etc. Rapid tooling is in this case used as a rapid prototyping method. Rapid tooling of a blow mold leads to the fast production of bottle prototypes.

The term rapid tooling is a subsection of additive manufacturing. It is used as an umbrella term for all novel technologies that allow for additive manufacturing of tools, mostly molds for polymer processing. These technologies include but are not exclusive to Polyjetting, selective laser sintering (SLS), stereolithography (SLA), digital light processing (DLP), continuous liquid interface production (CLIP) and fused deposition modeling (FDM) [7, 8].

The tools can first be created virtually as CAD models and are then turned into 2D renderings by a computer program that 'slices' the 3D model. These data are then sent to the 3D printer that produces the tools. This speeds up the prototyping process significantly and with that allows for faster implementation of new products into the production chain.

Table 1 - Rapid prototyping processes. The part quantity describes the quantity at which this process becomes economic.

[2]	Part quanitity	Material	Mold Cost	Part Cost	Lead Time
3D printing	1-10	FDM/Polyjet plastic		High	High
Machine Milling	1-100	Thermoplast		High	Medium
Silicone Molding	5-100	Thermoset	Low	Medium	High
Rapid tooling: Injection Molding using Polyjet 3D printed mold	10-100	Thermoplast	Low	Medium	Medium
Rapid tooling: Injection molding using Soft Tools	100-20000+	Thermoplast	High	Low	Very Low

3. 3D PRINTING TECHNOLOGIES

This chapter describes the most widely used 3D printing technologies. These can be liquid, solid or powder based. Liquid based processes produce parts by melting or polymerization. Solid based systems use material sheets which are bonded together by pressure, heat and an adhesive, e.g. laminated object manufacturing. Powder based systems produce parts by melting or binding powder together [9].

For rapid tooling it is important that the process is fast and accurate. Although, the blow molds are just prototypes, they should have a smooth surface and create bottles of a consistent shape which can be used for functional testing. In the last section of this chapter, the 3D printing technologies are compared based on the most important parameters.

3.1. STEREOLITHOGRAPHY (SLA)

Stereolithography is a process in which a liquid multifunctional pre-polymer is cross-linked by chain reaction. This reaction is initiated by free radicals which are formed due to exposure to certain light [9].

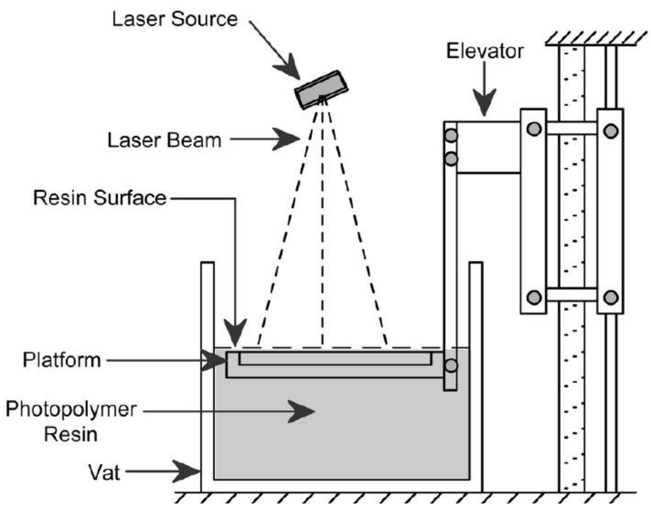


Figure 5 - SLA 3D printing machine (top-down process). Source: www.emeraldinsight.com

A stereolithographic system consists of a laser beam, a vat of photopolymer or resin, a building platform and mirrors to direct the beam. The platform is dipped into the vat after which the layer formed on top of the platform is exposed to the laser which cures the material selectively. The laser 'draws' the design onto the vat of resin line by line, layer by layer. After each layer, the build platform is dipped further into the vat of resin (top-down) in order to re-coat it with a new liquid pre-polymer layer. The building direction can also be bottom-up, meaning that the laser is applied from below and the platform is raised out of the vat. The printed objects should stay on the platform and not float around in the vat, the use of supports is thus required in almost all cases. These are printed structures of thin ribs only touching the object at the tips [10].

SLA is known as a very accurate but slow process. The speed of the process is mostly determined by the z-direction because the higher the object, the more layers need to be printed.

Stair stepping can occur due to thick layers or wrong orientation. Layer thickness can be too thick in lower resolution machines and/or due to higher viscosity material. If the laser beam is not perpendicular to the object surface, stair stepping is often visible as well. Manufacturers have developed algorithms in order to reduce this effect [11].

The object is rinsed with water and subsequently ethyl or isopropyl alcohol in order to remove excess resin. Furthermore, it is post-cured in a UV chamber in order to ensure complete polymerization and thus prevent warping, shrinkage or evaporation of VOC [11].

3.2. DIGITAL LIGHT PROCESSING (DLP)

Digital light processing is very similar to stereolithography. The light source in this case is however a high-definition projector. This means that a complete layer is flashed on the vat surface at once. The printing time is somewhat reduced compared to the SLA process. However, the projector creates volumetric pixels (voxels) which forms squares in the vat of resin creating pixelated edges in the printed object. 3D printed objects often have horizontal lines or steps. DLP printed object often also have vertical lines [12]. This effect can be resolved by sanding or bead blasting. Furthermore, extra algorithms for special layer cutting of the 3D image have been developed [10].

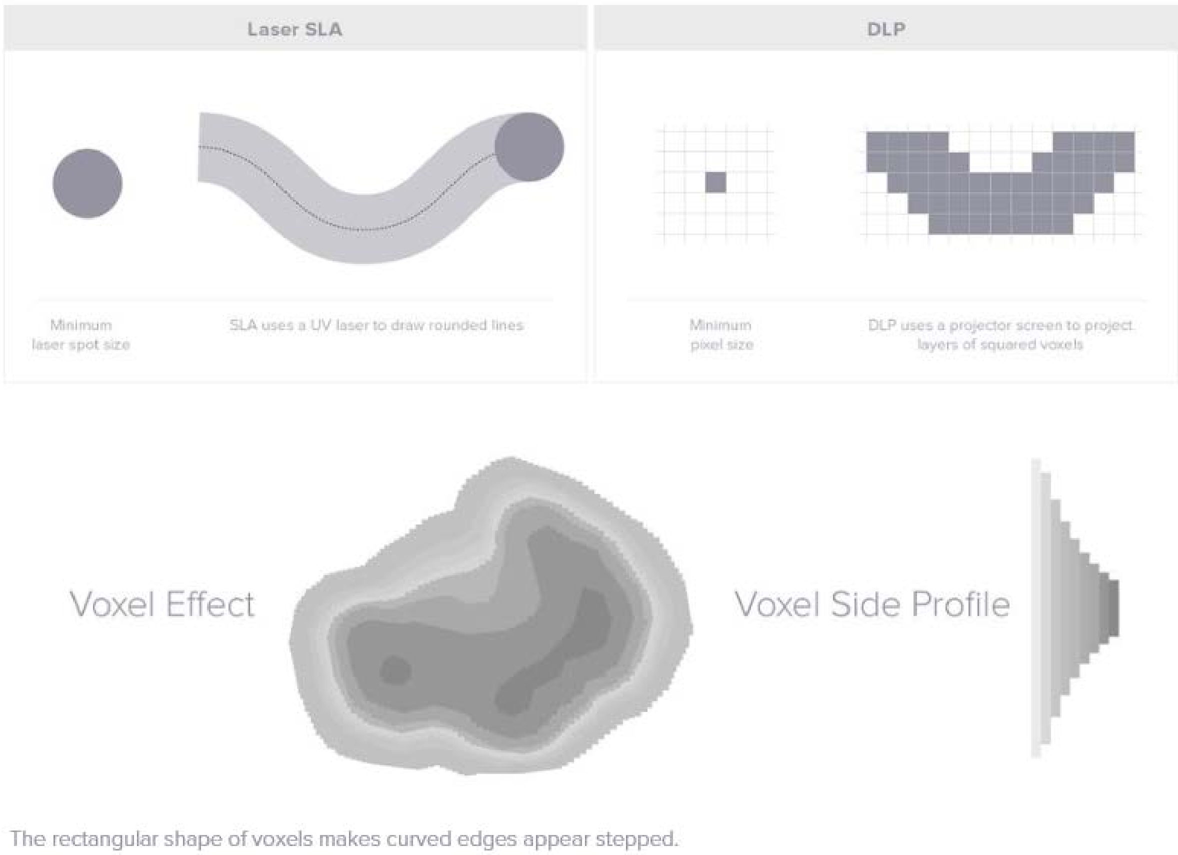


Figure 6 - Difference in resolution of SLA and DLP printed objects [12]

3.3. CONTINUOUS LIQUID INTERFACE PRODUCTION (CLIP)

CLIP is a continuous process which relies on the same principle as SLA or DLP. It begins with a vat of liquid photopolymer resin. Part of the vat bottom is transparent to ultraviolet light (the "window"). An ultraviolet light beam shines through the window, illuminating the precise cross-section of the object (see Figure 7). The light causes the photopolymerization of the resin just like with bottom-up SLA printing. However, in CLIP the object rises continuously and slowly enough to allow resin to flow under and maintain contact with the bottom of the object. In order to prevent the bottom layer of resin from solidifying directly at the window, an oxygen-permeable membrane lies below the resin. This creates a “dead zone” (persistent liquid interface). Photopolymerization is inhibited due to oxygen scavenging between the window and the polymerized part.

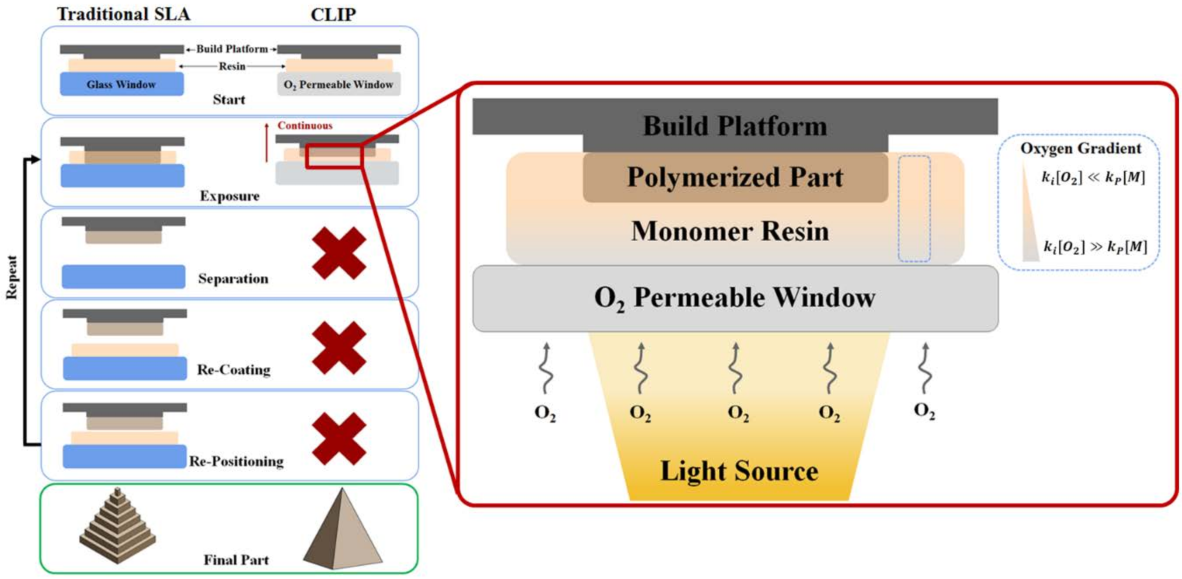


Figure 7 - CLIP process compared to SLA [13]

Unlike SLA, the printing process is continuous. Spreading of the next layer of pre-polymer (re-coating) is not necessary. The inventors claim that it ‘can create objects up to 100 times faster than commercial three dimensional (3D) printing methods’. Resolution of the printed part is supposedly also much better [13].

3.4. SELECTIVE LASER SINTERING (SLS)

SLS is a process that starts with an empty build platform. A thin layer of powder is coated on top of it and a laser selectively sinters the thin powder layer. One cross-section is now printed. The build platform now moves down into a bed, another layer of powder is coated on top and the process repeats layer by layer. To restrict the likelihood of parts warping or shrinking during printing, SLS printers use heated build chambers that heat up the powder to just below the sintering temperature. This does still however result in temperature gradients in large SLS parts where the bottom of the part has cooled while the recently printed top layers remains at an elevated temperature. To further mitigate the likelihood of

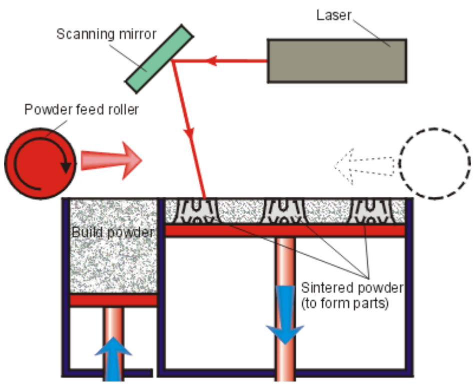


Figure 8 - Selective laser sintering process (Source: uni.edu)

warping occurring parts are left in the powder to cool slowly (often for 50% of the total build time).

SLS can create parts with high accuracy and can print designs with complex geometry. This is mostly because the powder remains in the bed and forms a support around the solid part. No additional support structures are required.

3.5. FUSED DEPOSITION MODELING (FDM)

FDM machines consist of an extruder head that applies polymer melt in a line, layer by layer. Each layer is printed as a set of heated filament threads which adhere to the threads below and around. Although the resolution, the machine can provide, depends on the size of the extruder head, the accuracy is not considered high enough for our application. The resulting surfaces are quite rough and would at least need to be sand or bead blasted [14]. Support material for FDM is only required with overhangs beyond 45°. The lines on each layer are printed slightly offset from the previous layer which allows for building of stable objects up to 45° angle [15].

3.6. POLYJET

A PolyJet 3D printer works like an inkjet printer. Instead of jetting drops of ink, the printer jets drops of photopolymer that solidify in seconds when exposed to UV light. These layers accumulate on the build tray until the part is complete. For complex geometries with overhangs, the 3D printer jets a removable gel-like support material. PolyJet materials properties vary, ranging from rigid to rubber-like. This technology can also mix multiple materials together to achieve unique material properties and colors. PolyJet materials are best suited for applications where accuracy, surface finish, and detail are essential components of the printed part.

3.7. COMPARISON

As the most important requirements for the rapid tooling to be of interest are the time and the likeness with the final product, the two most important criteria are the printing time and the surface roughness of the mold. A criterion that has not been addressed at all, is the material properties of the printed mold. In the comparison of the 3D printing technologies, this is however not yet of importance since all can process a variety of materials which is able to meet our needs.

Furthermore, it is important that (almost) no support material is required because this needs to be removed costing extra time and extra material. Post-processing includes sand blasting, bead blasting, polishing, …

For most 3D printing technologies, the direction of printing influences the tensile strength of the resulting part. For some processes more than others (see Figure 9). As you can see, the biggest difference in tensile strength is observed in polyjet printed parts. Each layer cured by UV light is stronger than the bond formed between the layers. For stereolithographic systems, the opposite seems to be true.

Table 2 - Comparison of 3D printing technologies

	Printing time	Surface	Cost	Support Material	Post-Processing
Polyjet	-	+	-	-	-
FDM	-	--	0	--	--
SLA	--	++	+	-	-
SLS	-	-	--	++	--
CLIP	+	+	-	++	-
DLP	0	-	0	-	-

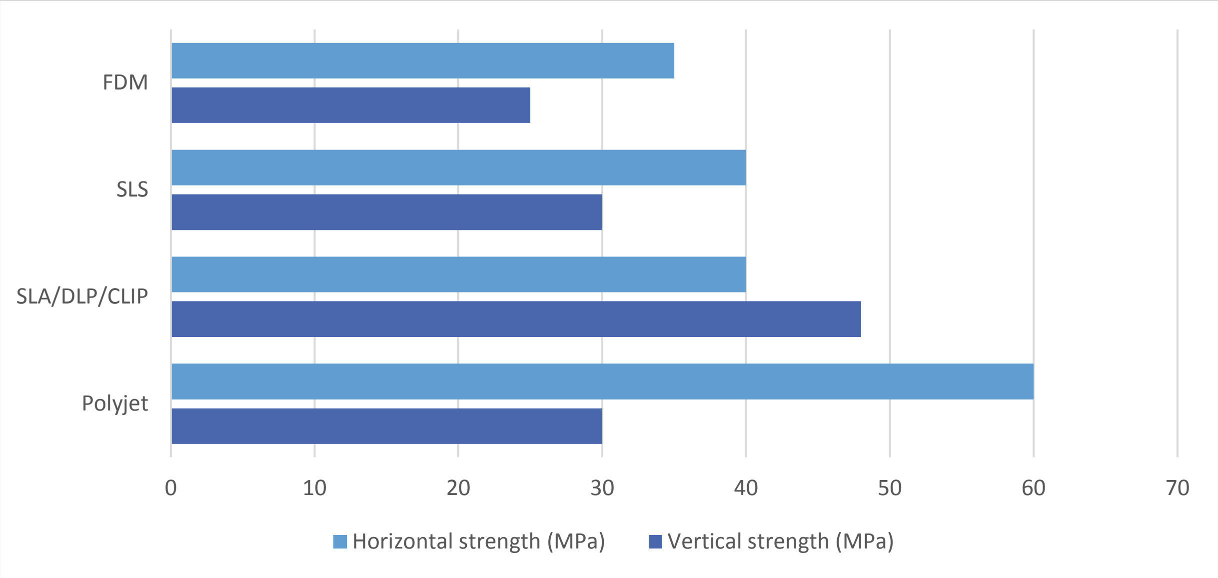


Figure 9 - Tensile strength of various 3D printing processes [9]

From this comparison, it seems like CLIP is the most promising 3D printing technique. It needs to be taken into account, however, that suppliers have polyjet printers available and a lot of experience has been gained using this technique for rapid tooling of injection and blow molds. Currently, the most widely applied process is the Connex polyjet machine using green digital ABS provided by stratasys. Another issue to consider is that not all printers can process any type of material. As will be discussed later, the material has to have a good heat resistance and needs to be able to withstand a certain pressure. Different molds made by different processes and materials should be tested in blow molding operation to show which one is actually most feasible.

Furthermore, it would be best to invest in an in-house 3D printer. This printer will not be bought with only this application in mind. Thus, the printer should be able to easily process a variety of materials. Polyjet printers are able to do this. However, those types are quite expensive. SLA, CLIP and DLP are also able to do that. However, suppliers of these machines do not provide many materials with high heat resistance. Development towards material improvement and variety is ongoing.

4. MOLD DESIGN

In general, the mold needs to be the outer shape of the product to be blown and should include all details in negative form like raised logos, etc. It is constructed of two halves that are joint after the parison is placed in between them. However, it is not that easy. Many details need to be taken into account as well.

For the two halves to be oriented correctly, mold guide pins and corresponding holes are introduced in the mold (see Figure 10). On the top of the mold (where the blow pin enters), a striking plate of a strong material is installed in order to ensure that the force of the pin striking the mold does not cause fragmentation or displacement of the mold halves. Furthermore, cooling channels and vent locations are required.

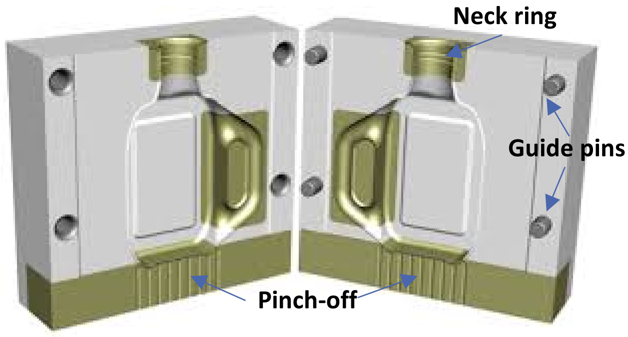


Figure 10 - Example of a blow mold [15]

4.1. CONCEPTS

There are two possible mold designs. Either the entire mold is 3D printed without any cooling channels or a standard steel frame is used with just a printed insert of the bottle shape (see Figure 11 and Figure 12). The frame could include cooling channels in order to improve heat transfer and increase cycle time. Both of these concepts are modular in order for any mold to fit in any blow molding machine. This way, the prototyping process is no longer limited to supplier capacity since the mold can be used by any supplier with available capacity.

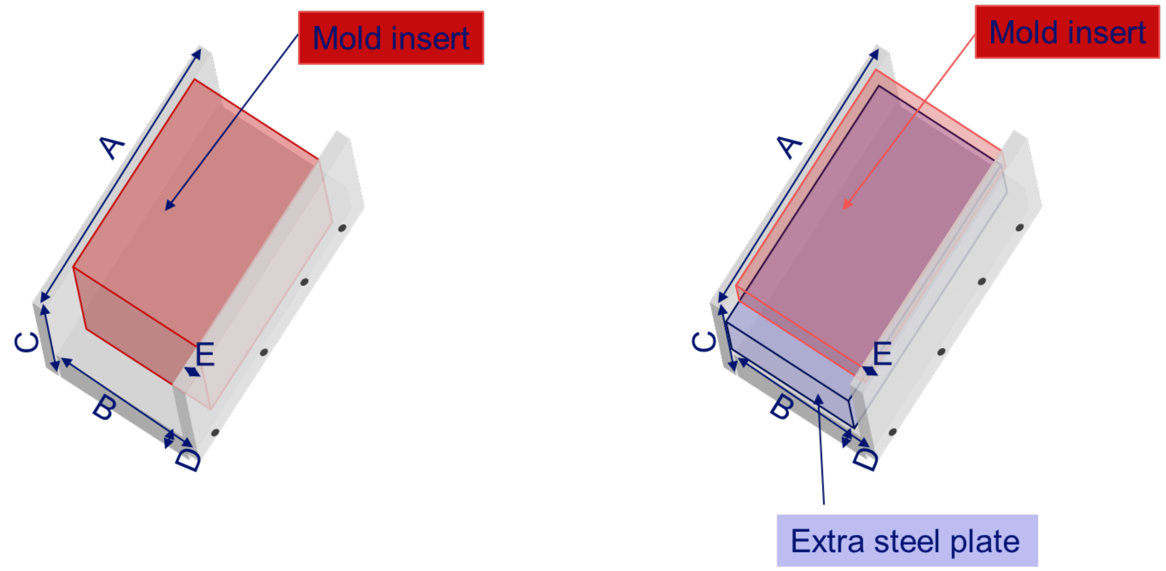


Figure 11 – Modular standard steel frame

Figure 12 - 3D printed mold inserts in a standard steel frame [15]

The mold is fixed in the blow molding machine by at least two bolts on the back of each half. A standard steel frame as proposed by stratasys (see section 4.4) could incorporate these bolts at different locations, fitting most machines. Another option would be to provide every supplier with standard steel plates that can be placed behind the 3D-printed molds.

The fixation points and guiding pins can be the same for both concepts. However, the steel frame concept makes it possible for these features to be made of steel which can guarantee a longer life time of the tool. Furthermore, operating issues like expansion, mold orientation, etc. are more similar to current operating conditions. For example, guiding pins made of plastic are more elastic. It is thus more likely that the two mold halves might shift during mold closing, creating a warped bottle.

It should also be easy to make the 3D CAD model of the bottle. It should be developed such that it has a standard framework (block shape with centering features, etc.) and only the bottle shape needs to be built up inside that framework. It would be easiest to have one or two standard neck ring inserts for the bottle closure (as shown in Figure 18). This is easier because the development of a certain neck ring will take more time and they are more likely to break during operation. It would thus be better to have them made out of a more durable material like steel. This neck ring insert can be used in a printed mold with back plates or with a printed insert in a steel frame.

As described earlier, a striking plate is needed to withstand the force exerted when the blowing pin hits the mold. This plate can be the same for each mold and is required for both concepts.

4.2. COOLING

The cooling stage of the blow molding process takes up about 2/3 of the complete blow molding cycle [16, 3]. According to literature, effective cooling is vital to decreasing cycle time and thus increasing productivity [3] and a lot of research is being done towards better cooling channel design.

Cooling in blow molding depends on coolant temperature, thickness distribution of the container, coolant flow rate, heat conduction between the mold surface and the cooling channel surface, heat convection by the coolant, cooling channel size or position, etc. [3]

The cooling channel design can influence the part quality. Cooling of the mold cavity surface or parting surface will result in better finish along the parting lines. Accurate design of the distance between the cooling channel surface and the mold surface can decrease the risk of hot spot or severe shrinkage. Usually, the design of the cooling channels is simple (straight-line drilled), but literature research suggests that another approach should be chosen [3]. It seems obvious that by 3D printing the mold, a much more complicated cooling channel design can be chosen. A lot of research is being done towards most efficient cooling channel design [17, 18]. These are most often conformal along the bottle mold shape. This way the smallest distance between bottle and cooling channel is realized, thus decreasing the thermal resistance and making heat transfer most efficient.

4.2.1. HEAT TRANSFER

Since pretty much all 3D printing materials retain heat, cooling of the blown part will be difficult. Stratasys, a 3D printer supplier, has suggested some possible designs to improve cooling. Most importantly, they recommend a standard steel form in which only 3D printed inserts need to be placed. This standard frame can supposedly remove heat via integrated cooling channels. However, cooling channels can easily be placed conformal to the shape of the mold if they are included in the 3D printed design. It remains to be analyzed if there is any advantage to this type of design.

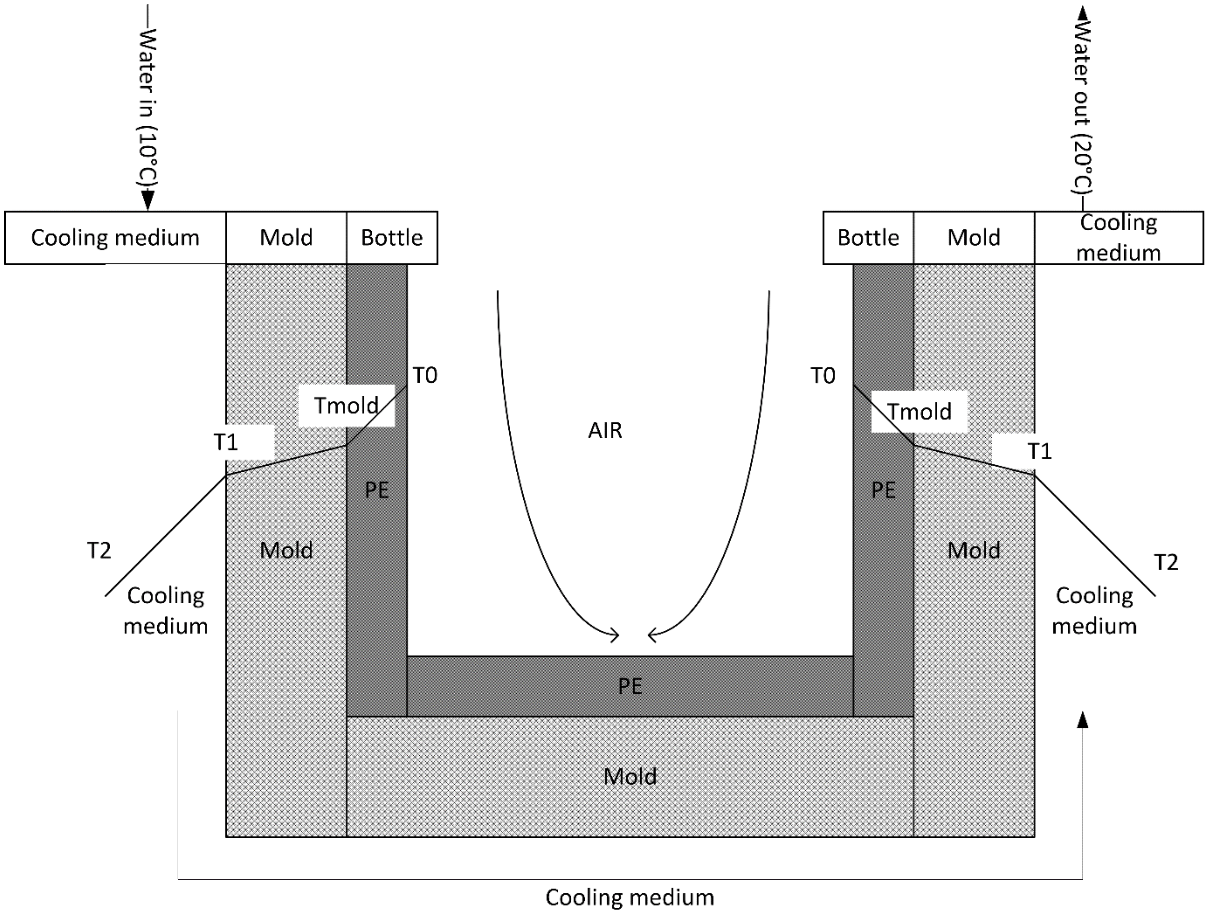


Figure 13 - Simple Scheme of Heat transfer

A simple scheme of the heat transfer during blow molding can be seen in Figure 13. In this simple model, the heat transfer is treated as it is in a steady state heat exchanger. The hot thermoplast melt is blown into the mold and conforms to the mold surface. The temperature it has at the mold surface is lowered by convection of heat from thermoplast melt to the mold surface, conduction of heat through the mold wall thickness and then convection of heat to cooling water or cooling air. Steady state is assumed to be reached over the average of multiple cycles. Obviously, this gross simplification to a steady state situation is invalid for the calculation of the exact heat transfer. However, since we just want to have a comparison between different heat transfer situations we assume this is enough.

The overall heat transfer coefficient can be estimated according to the following equation [19]:

Equation 1

$$\frac{1}{UA} = \frac{1}{h_1.A_1} + \frac{t}{k.A_2} + \frac{1}{h_2.A_3}$$

Table 3 - Parameters used in Equations 1 and 2

Parameter	**Description**	**Unit**
UA	Overall heat transfer	W/K
h_1	Convective heat transfer coefficient PE to mold	$W/m^2.K$
A_1	Heat transfer area (mold inner surface)	m^2
t	Thickness of mold wall	m
k	Conductive heat transfer coefficient of mold material	W/m.K
h_2	Convective heat transfer coefficient mold to cooling medium	$W/m^2.K$
A_2	Heat transfer area (mold outer surface)	m^2
Q	total heat transferred	W
ΔT	Overall temperature difference	K

From Equation 1, the total heat transferred can be calculated via

Equation 2

$$Q = UA.\Delta T$$

From equations 1 and 2 we can see that the only parameters to adjust in order to improve cooling performance is the heat exchange area, the cooling medium (thus changing h_2) and the temperature of the cooling medium (thus changing ΔT). In order to increase heat transfer, the heat exchange area on the outer mold surface, A_3, can be changed (not the inner one because it is needed to create the correct bottle shape/surface). This can be done by making the surface ribbed, adding wafers etc. (examples can be seen in the pictures below).

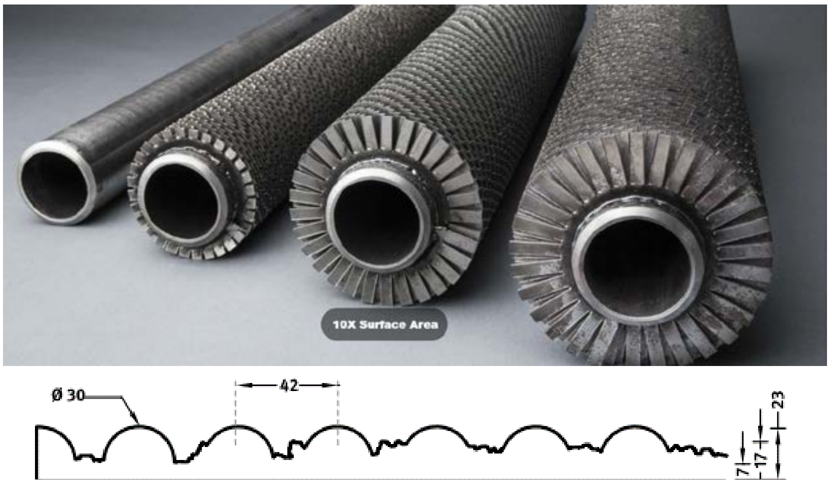


Figure 14 - Different ways of increasing heat transfer area.

In order to compare if any advantages can be achieved by introducing cooling channels conformal to the mold, increasing the heat exchange area or choosing a different cooling medium, the total heat exchanged is calculated and shown in Figure 15. See Appendix 1 for the complete calculation and all assumptions.

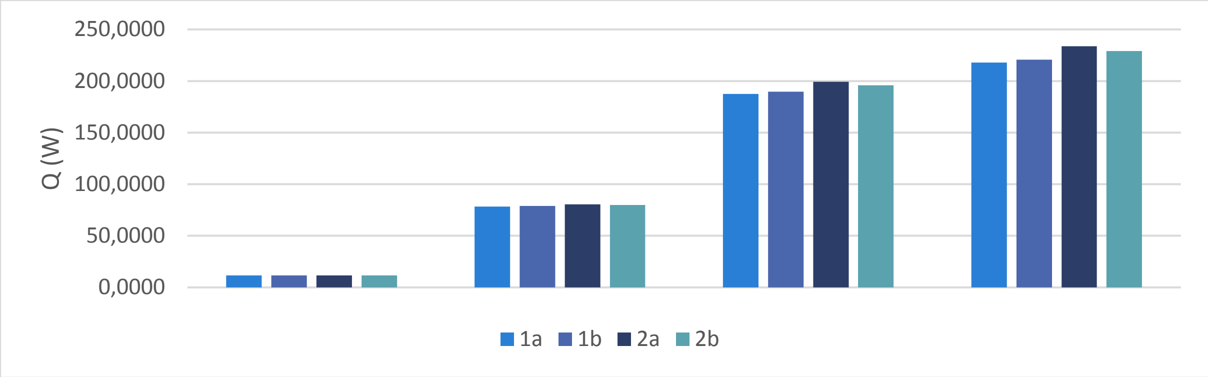


Figure 15 - Comparison of heat exchanged with different cooling media and suface areas. 1: cooling medium is air / 2: cooling medium is water / a: non-ribbed surface / b: ribbed surface.

As you can see, the total heat exchanged increases according to 1a<1b<2b<2a. It does increase by increasing the surface area and using water instead of air. Increasing the surface area by using a ribbed surface, also automatically increases the wall thickness due to the shape of the wall (see Figure 14). This is why the increase in surface area does not result in a higher amount of heat exchanged for water (see Appendix 1 for further explanation). However, the influence is very small. The increase in total heat exchanged is maximally 0.4% (from 1a to 2a).

This very low influence implies that the conductivity of the material is so low, that the determining factor is not the surface area, the cooling medium or the temperature difference. The steady state situation is presumably never reached. In order to compare the 3D printed mold material to steel or aluminum frames, the time required to heat up the entire mold (to the temperature of the blown PE inside) is calculated. This time represents the point at which steady state is reached.

The time required to heat up the mold can be calculated to be (see Appendix 2 for the entire calculation) [20]:

Equation 3

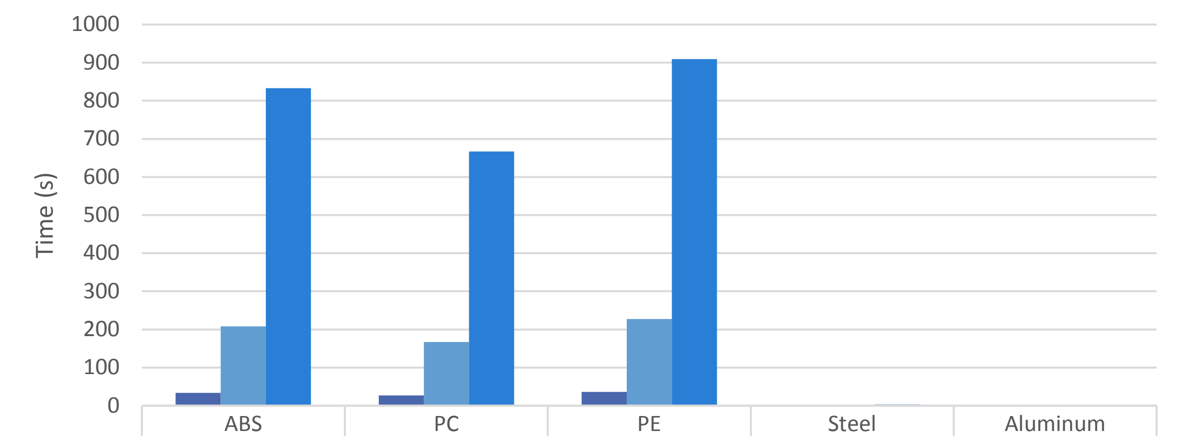
$$\tau = \frac{\rho c_p}{k} . d^2 = \frac{1}{\alpha} . d^2$$

α represents the value of thermal diffusivity which is a parameter that can be found in literature for a lot of construction materials.

Table 4 - Thermal diffusivity of different materials [21, 22, 20, 23]

Material	**Thermal diffusivity (mm²/s)**
ABS	0,12
PC	0,15
PE	0,11
Steel	8 - 67
Aluminum	97

From these we can make a comparison in times to heat up the mold:



	ABS	PC	PE	Steel	Aluminum
2 mm	33	27	36	0,2	0,0
5 mm	208	167	227	1,0	0,3
10 mm	833	667	909	3,8	1,0

Figure 16 - Time required to heat up the tool at different mold wall thicknesses (2mm, 5mm and 10mm)

This analysis shows that common 3D printing materials like ABS and PC have such a high thermal resistance that cooling is pretty much not feasible via cooling channels in 3D printed molds. Some companies suggest from experience to just increase the cycle time and let the mold cool by ambient air. In order to prevent the mold from heating up, it is also suggested to cool the mold by pressured air in between cycles.

Currently, pressurized air is often already used during the cycle (second stage in Figure 3). This cools the bottle from inside as well. This air is called 'purge air' because it purges most of the heat from the system. This is done in order to reduce cycle time and/or prevent hot spots and deformation of the bottle. If such a feature is not available, the mold can just be cooled in between the cycles by pressurized air after the two halves are separated.

Using special, more conductive material, cooling can be made easier. When using SLS, metal powder can be sintered. Altaf et al. have tested the use of aluminum-filled epoxy material for injection molds [17]. They found that cooling time could be reduced by about 66% by introducing an aluminum insert between the mold cavity and the cooling channel. While this approach might be interesting for future investigation, current commercial techniques are investigated in this paper.

Unless the mold wall thickness can be reduced significantly (to about 2mm), the steady state situation is not reached within a reasonable time frame. It can be concluded that cooling channels do not need to be incorporated in the mold.

4.3. VENTING

When the mold closes, a certain amount of air is captured between the parison and the mold cavity. When the parison is expanded, the captured air can cause the polymer melt to not completely conform to the mold surface. This will lead to visible abnormalities on the surface of the blow molded product and poor mold cooling. Venting slots are typically located at the edge of inserts in the cavity. Furthermore, porous materials are often used. Both venting slots and porous channels can produce visible markings on the product which is why texture, inserts etc. can be used to mask the markings [6].

4.4. STRATASYS' RECOMMENDATIONS

Stratasys is a big supplier of Polyjet and FDM machines and materials. They have gained a lot of experience in rapid tooling as well and made a few white papers on the topic available to the public. Some recommendations specific to FDM printed molds which might also be applicable to molds printed by other 3D printing technologies.

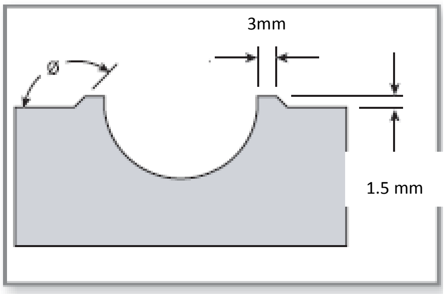


Figure 17 - Raised rib on the contour of a cavity [15]

Venting slots are not necessary because the porosity of the mold material provides enough venting. Furthermore, according to stratasys, the addition of a sloped, raised rib on the contour of the cavity (see Figure 17) is advisable. This rib acts as a compression seal between the mold halves, which gives clean shut-off and good pinch-off of the parison.

They also recommend the use of 3D printed inserts instead of printing the complete mold out of PC (see Figure 12). The FDM inserts are placed inside standard aluminum or steel mold bases. Standard cooling lines are incorporated in the mold base. The mold bases have a rectangular cavity in which the FDM inserts need to fit perfectly. Another option is to make the FDM inserts such that they fit on the contact line of the two mold halves with a certain periphery but on the back and front end the FDM mold follows the mold form. This way, an air gap is left between aluminum mold base and FDM insert. This allows for more extension or contraction of the FDM insert during the heating and cooling stages. This in turn leads to lower risk of stress fractures. Furthermore, cooling is faster since the insert retains less heat [1].

These last suggestions are addressed further in the next section.

4.5. FLEXIBILITY

Another important issue in mold design is keeping flexibility of bottle suppliers. This implies that the mold needs to fit in any blow molding machine, whichever one is available. The mold is fixed in the blow molding machine by at least two bolts on the back of each half. A standard steel frame as proposed by stratasys could incorporate these bolts on different spots, fitting most machines. Another option would be to provide every supplier with standard steel plates that can be placed behind the 3D-printed molds.

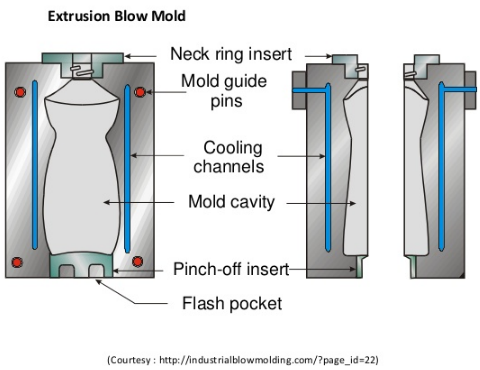


Figure 18 - Schematic view of extrusion blow mold

The two mold halves are clamped between two plates. The depth of the mold needs to be big enough, such that the machine can hold it in place with enough pressure (clamping distance). The clamping distance can vary between suppliers. A steel backplate or standard steel frame should be readily available at every supplier. These can help ensure that the minimum clamping distance is always reached and that the mold can be placed in any blow molding machine.

In order to see how much the different molds might vary in depth, the depth of most current bottles have been summarized. The mold depth has been calculated by dividing the bottle depth by 2 (since there are two mold halves) and adding 10mm wall thickness of the mold. The x-axis shows the volume of the bottle in ml. As you can see most bottles do not vary much. If the backplate or standard steel frame is made such that it holds depths of about 40mm, the bottles with depths lower than that can be used with an additional small backplate or could be printed with a thicker mold wall in order to fit and ensure good clamping. The ones with higher depths up to 61mm should be fine with the same backplate as the minimum clamping distance is definitely reached.

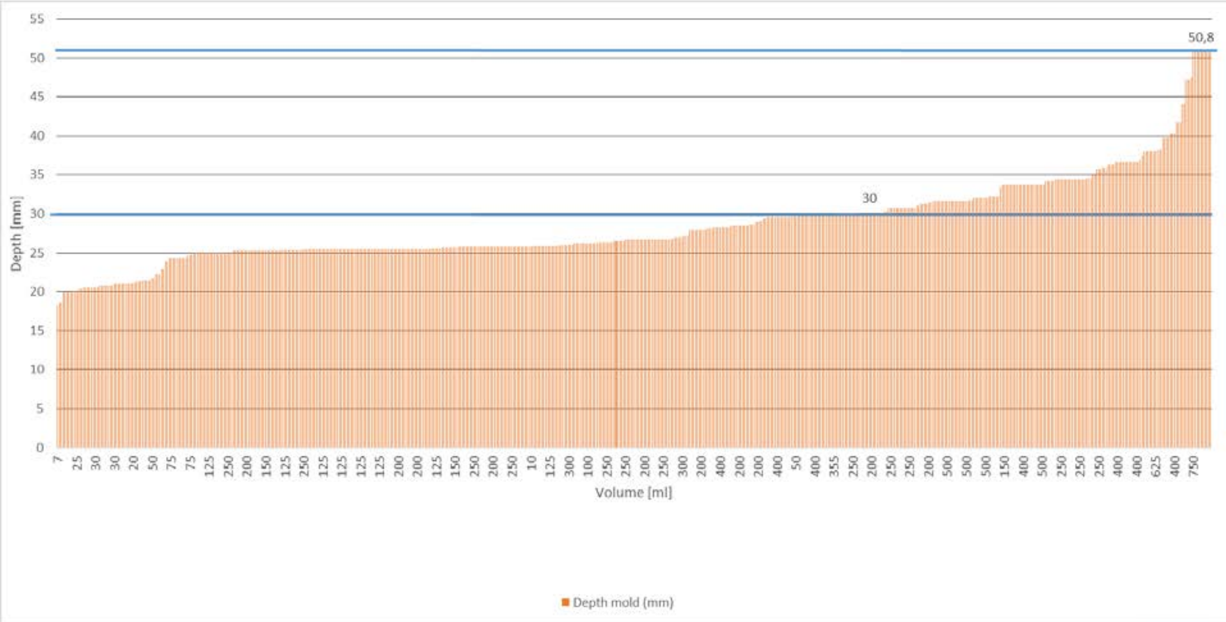


Figure 19 - Range of mold halve depth dimensions in mm. X-Axis shows the bottle volume. Y-Axis shows the depth of the bottle + 10 mm mold wall thickness.

The minimum clamping distance describes the distance between the two clamping devices that are holding the mold inside the machine (see Figure 20). These clamping devices need to exert a minimum amount of pressure to the mold in order to close the mold completely. If the mold is not closed well enough, a seam will be visible on the bottle. The minimum depth of the mold that is needed, i.e. the minimum clamping distance, varies between blow molding machines.

The lowest standard available at one of the biggest suppliers is 100mm. The largest mold halve is about 50mm deep (assuming a wall thickness of 10 mm and no extra frame or support). These would fit exactly in the smallest machine with clamping distance of 100 mm. All the other molds require back plates or a frame in order to arrive at the required 100mm depth. Standard steel backplates of sizes 30mm, 40mm and 50mm thickness should thus be available at the supplier's. These plates can help realize the depth of the bottle molds illustrated in Figure 19. The printed mold halves should always be designed to have a depth (X) of:

$X + F*30mm + G*40mm + H*50mm = 100mm/2$,

Where F, G, and H are constants that equal 0, 1 or 2.

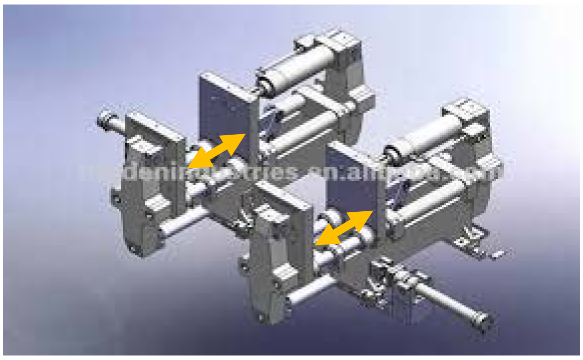


Figure 20 - Example of a clamping device in a blow molding machine. (seekpart.com)

If a standard steel frame is used with printed mold inserts, the frame should also be developed customizable in height and width, i.e. modular. As discussed, the printing time will increase due to larger parts that need to be printed. Furthermore, the larger the printed mold insert, the worse the heat transfer. Thus, the steel frame should not be one block but should be assembled of a backplate, two sides, a neck ring insert, a striking plate and possibly a bottom plate. Plates of different length, height and thickness should be available and put together to fit the smallest possible mold insert (see Figure 11).

In order to get an idea of how many steel plates are needed and what dimensions are needed, the height and width of bottle molds are calculated by adding 10 mm mold wall thickness on each side and summarized in Figure 21 and Figure 22.

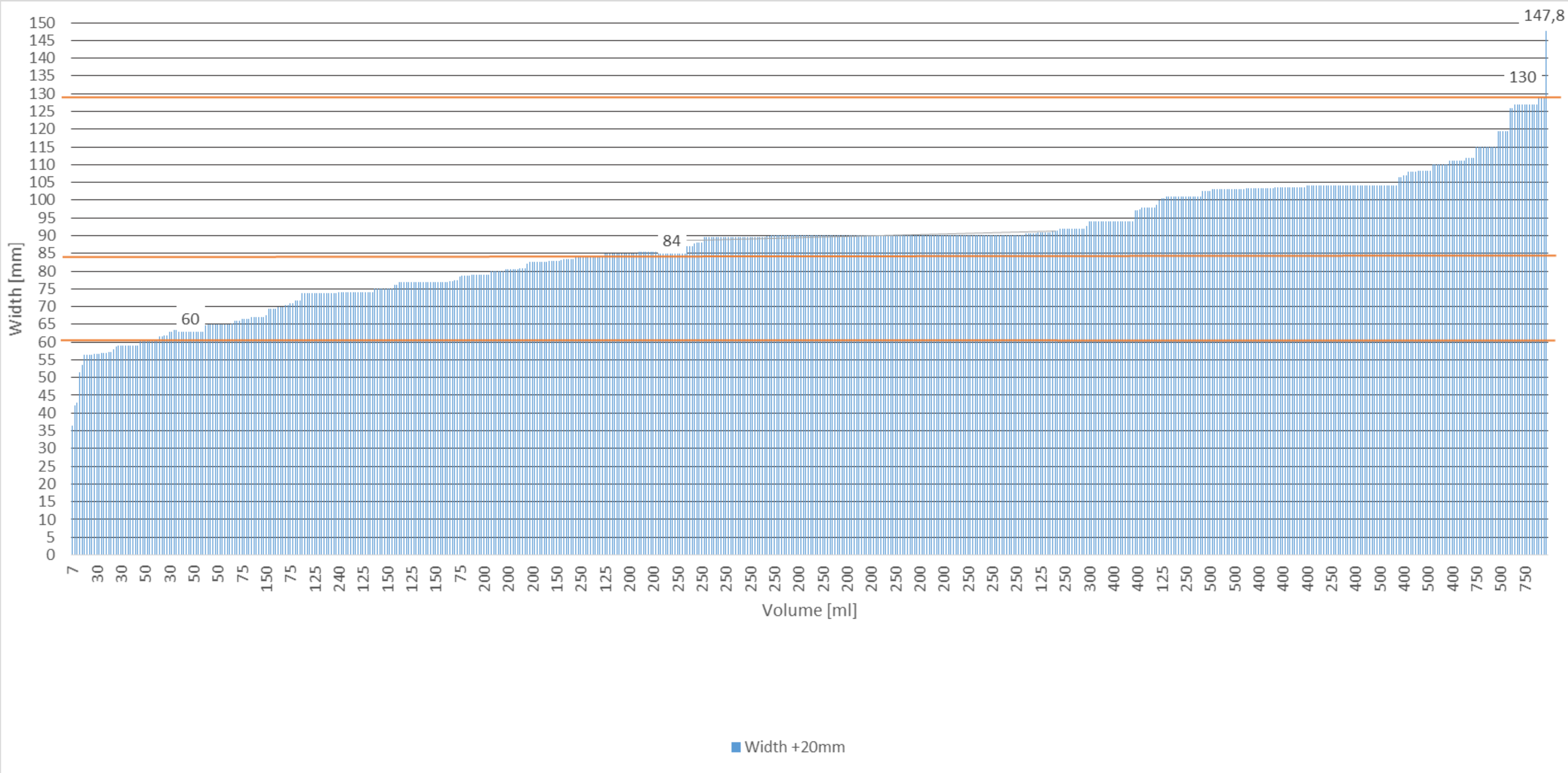


Figure 21 - Range of mold width dimensions in mm. X-Axis shows the bottle volume. Y-Axis shows the width of the bottle + 20 mm mold wall thickness.

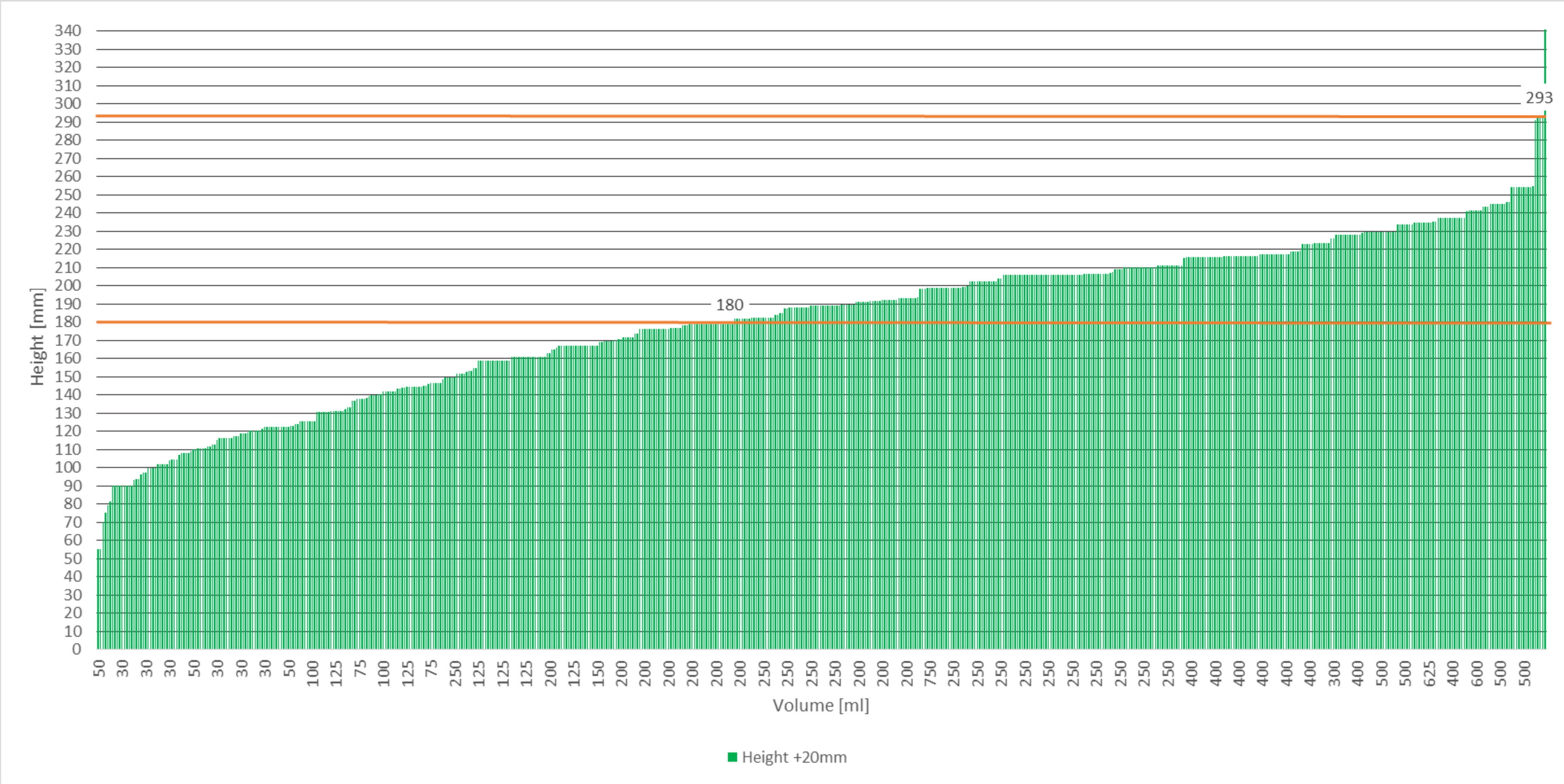


Figure 22 - Range of mold height dimensions in mm. X-Axis shows the bottle volume. Y-Axis shows the height of the bottle + 20 mm mold wall thickness.

10 mm standard bottom plates and 20 mm standard side plates are required to create a modular frame design (see table below). Furthermore, enough bolts are needed such that the frame can withstand the operating pressure. It remains to be tested experimentally if more features like guiding pins or additional bottom plates are required in order to keep the printed mold centered.

Table 5 - Standard plates for a modular standard steel frame. Dimensions in mm according to parameters shown in figure above.

Mold insert size			Standard bottom			2X Standard sides		
Height	Width	Depth	A	B	D	A	C	E
293	84	50	293	84	30	293	80	30
293	84	30	293	84	20	293	80	30
293	130	50	293	130	30	293	80	30
293	130	30	293	130	20	293	80	30
180	60	50	180	60	30	180	80	30
180	60	30	180	60	20	180	80	30
180	84	50	180	84	30	180	80	30
180	84	30	180	84	20	180	80	30
180	130	50	180	130	30	180	80	30
180	130	30	180	130	20	180	80	30

4.6. CONCEPT SELECTION

Both concepts have their advantages and disadvantages. Both concepts provide maximum flexibility while the standard steel frame requires a larger investment. All of the modules (back plates, side plates, bolts, neck ring inserts,…) need to be provided for each supplier. The first concept only requires 3 standard backplates. Furthermore, the design of the standard steel frame is more complicated.

The standard steel frame does provide the possibility of incorporating cooling channels. However, it has been shown that these would not provide much more cooling due to the high thermal resistance of the printed mold material. The concept without a frame requires a lower investment to provide more flexibility. Thicker mold wall thickness might be required for the mold to withstand the clamping and operating pressures. It might be feasible to further reduce the mold wall thickness of the inserts in a steel frame because it might provide additional strength to the tool.

It is recommended to first try the concept without the steel frame and try to find the limit of the wall thickness and material strength. The 3D CAD model should be made as simple as possible in order to adjust it for any bottle shape. A steel frame can later always be added if necessary.

5. MATERIAL SELECTION

As the previous section mentioned, a certain material strength is required for blow molding operation. The better the mechanical properties of the material, the thinner the mold wall can be, the faster heat transfer and cycle time might be and the less 3D printing material is required.

Blow molds for large production scale application are typically made of stainless steel. Prototypes are mostly cut from aluminum. In order to reduce prototyping time, additive manufacturing technologies have recently been employed. Different materials are being used. Most typically acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polystyrene (PS), or polycarbonates (PC) are used in these applications. In SLS, different powdered materials can be added. Often these are powdered metals like aluminum or iron. These can improve the thermal or mechanical properties of the mold. From supplier experiences, it can be said that both polycarbonate (PC) and green digital acrylonitrile butadiene styrene (ABS) provided by stratasys work well for blow molding applications.

Table 6 - Material Properties of typical MoC for blow molds [5]

Material	Rockwell Hardness	Density (g/cm^3)	Conductivity ($W/m^2.K$)	Tensile Strength (MPa)
Steel				
P-20 T51620	28-50C	7.86	38.1	1007
Aluminum				
6061 –T6 A96061	60B	2.71	166.9	276
7075-T6 A97075	88B	2.80	129.8	462

Table 6 shows typical material properties of conventional blow molds. These tools can have life times of up to 20 years. Thus their properties may not be the ones that are needed for the printed prototype blow molds. The thermal properties should be as similar to stainless steel or aluminum as possible in order to ensure good cooling and prevent hot spots and deformation. The mechanical properties should be such that the mold can withstand the operating pressure at the operating temperatures. It is sufficient if it survives 20-30 cycles to provide some prototype bottles.

Figure 23 and Figure 24 compare the heat deformation temperature (HDT), the tensile modulus and the tensile strength of various 3D printing materials. Some are designated for the use in DLP, some in CLIP, some in FDM and some in the Polyjet process. The materials that are known to work, i.e. green digital ABS for Polyjet and PC for FDM, are highlighted in orange.

While the temperature of the parison is known to be about 120°C when leaving the extruder head, it is unknown what the temperature on the mold surface will be. Thus, the actual required thermal stability of the mold material remains to be proven experimentally. As you can see in Figure 23, the HDT of the digital ABS which is known to work is around 80°C. It remains to be proven experimentally, if cheaper materials with worse thermal properties may also work.

Another important issue for material selection is their processability. Each 3D printing technology, each 3D printing machine, and each 3D printing supplier, has their own range of materials that they provide. For example, Connex machines by stratasys offer big flexibility concerning the types of materials that can be printed with. SLA or CLIP suppliers usually offer machines that can only deal with a much smaller range of materials. These types of technologies have not been used for rapid tooling in the past, but rather for the production of rubbery, soft tools or prototypes.

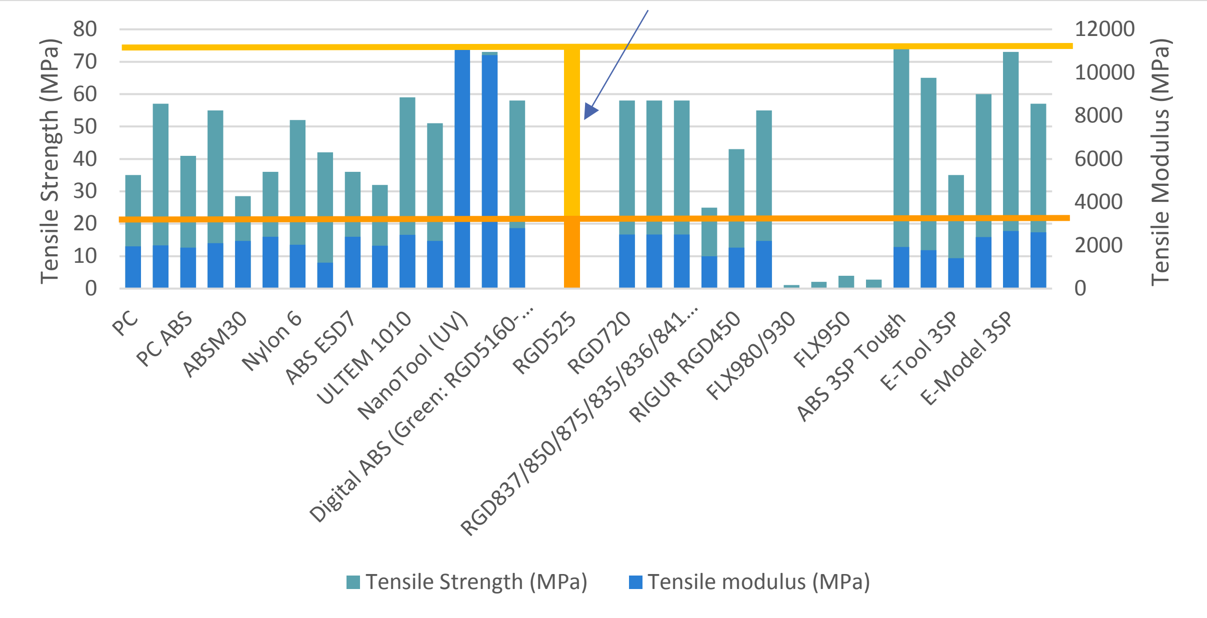


Figure 23 – Tensile strength and modulus of various 3D printing materials used in FDM, Polyjet and SLA printers. Data provided by stratasys, envisiontec and DSM.

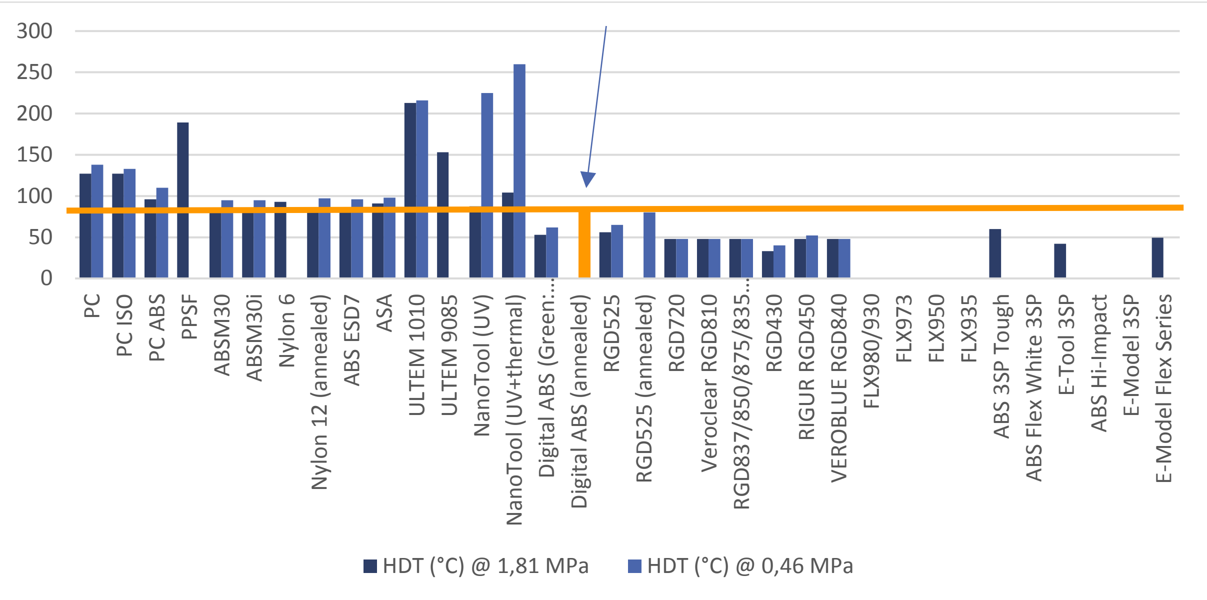


Figure 24 - Heat deformation temperature of various 3D printing materials. Data provided by stratasys, envisiontec and DSM,

In order to come to a selection of materials, all available values are firstly compared to that material which is known to work, i.e. those that are highlighted in the figures above [1]. Going from these material properties, i.e. HDT (at 0.46MPa) = 80°C, Tensile strength = 75MPa and tensile modulus = 3300MPa, suited materials should be selected.

Obviously, the mold should not deform (warp, shrink, expand, etc.) during the blow molding cycle. Thus, HDT should be higher than or as high as that of the digital ABS. Furthermore, the mold should not break or tear during the blow molding cycle. Thus, tensile strength and modulus should be as high as possible. Stratasys for example claims that thermal properties of unannealed ABS and polyphenolsulfone, typical materials in FDM applications, are insufficient. They claim that in order to use the tool for 1000 cycles, PC is the material of choice.

An argument is to be made that the mold is only exposed to high pressures and heat for short cycle times. Furthermore, the mold only needs to be able to produce 30-100 bottles. If the material does not completely heat up and is cooled well in between cycles, as is assumed in section 4.2.1, lower HDT values might be acceptable as well. This should be determined experimentally. The mold should be printed out of different materials with different 3D-printing technologies, i.e. Polyjet, SLA and CLIP. Then a line trial could be run for each prototype mold to see which one works best and produces the most representable prototype bottles.

6. SOME COMMENTS ON ECONOMIC FEASIBILITY

The rapid tooling process should not be much more expensive than the current process. An investment of more money might be reasonable when time can be spared.

While a specific economic picture cannot be disclosed, it can be said that, at the current state of knowledge, rapid tooling by the 3D printing lies within the same price range as the current prototyping process of cutting aluminum pilot blow molding tools.

7. CONCLUSION & RECOMMENDATIONS

Prototyping is one of the most costly and time consuming processes in developing novel packaging ideas and concepts. This report investigates rapid prototyping of cosmetic bottles via 3D printing of prototype blow molds. The requirement is to reduce lead time of new prototypes to a time span of 5-7 days at similar prototype cost. Furthermore, the mold needs to have a lifetime such that it can produce 30-100 prototype bottles.

Currently, the most widely applied process is the Connex polyjet machine using green digital ABS provided by stratasys. It is shown that this process and material might be more expensive and time consuming than DLP or CLIP with a cheaper and less qualitative material. It is recommended at this point to produce blow molds via polyjet, DLP and CLIP. If cheaper metal powders surface in the market, the SLS process would produce molds with much better thermal and tensile properties. Supplier experience should be a guide in material selection. If there is an economic advantage, materials with worse mechanical and thermal properties can be tested as well.

A concept for a mold design has been developed. There are two options. One is to use a standard steel frame containing cooling channels and fixation points in which only a printed bottle form is printed (mold insert). The other is to print the entire mold and only use steel plates to fix the mold in the blow molding machine. Both systems are modular. Currently, printing the entire mold seems to be more advantageous. It requires less investment and also seems much easier to implement. An advantage of using a steel frame would be the possibility of including cooling channels in it. However, cooling by water through cooling channels does not work due to the low thermal conductivity of the printed mold material. Possibly, the steel frame would allow for thinner mold walls which would also be advantageous because it would reduce material cost. It is recommended to start developing a mold design without a steel frame. A steel frame can always be added later and experiments to reducing wall thickness and introducing cooling channels can be set up.

In conclusion, rapid tooling of blow molds is possible and could reduce the lead time of prototype bottles significantly by creating more flexibility in the supply chain, i.e. the mold can be used by any supplier to produce the prototype bottles. At the current state of knowledge, rapid tooling via 3D printing lies within the same price range as cutting prototype molds from aluminum.

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APPENDIX 1 – ESTIMATION OF HEAT TRANSFER

Assumptions:

1. Steady state situation: Heat flow through the tool is constant. Heat flow in=Heat flow out.
2. The bottle and mold have a cylindrical shape of dimensions shown in Table 7.
3. The mold wall thickness is reasonable at 10mm.
4. The value of thermal conductivity h_1 between PE and mold is unknown. It is assumed that it does not influence the comparison between the heat transfer situations (is confirmed later).
5. There is no heat loss to the surroundings.
6. The temperature at the mold surface is the average between the temperature of the PE melt and the mold temperature.
7. The PE melt can be treated the same as a flowing fluid (like in a heat exchanger situation).

These are a lot of assumptions of which quite a few might not be valid but this calculation is just meant for an estimation of the influence of parameters, like the surface area or cooling medium, on heat transfer rate.

Heat transfer rate can be calculated via:

$$Q = UA.\Delta T$$

The overall heat transfer rate can be estimated when applying Fourier's law in series:

$$\frac{1}{U.A} = \frac{1}{h_1.A_1} + \frac{t}{k.A_2} + \frac{1}{h_2.A_3}$$

The surface areas are calculated according to the area of an open cylinder (open at the top):

$$Height * 2\pi * Radius + \pi * Radius^2$$

The input of values can be found in the table below.

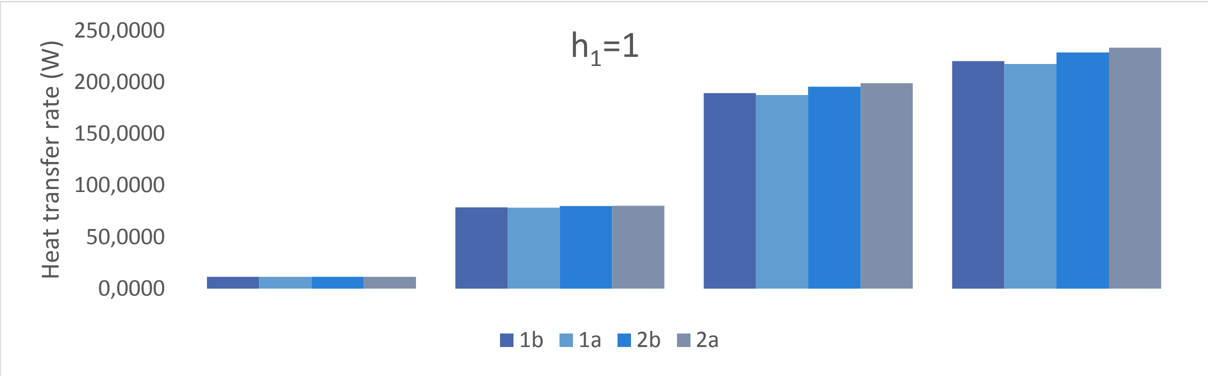
Table 7 - Parameters and values used for heat transfer estimation

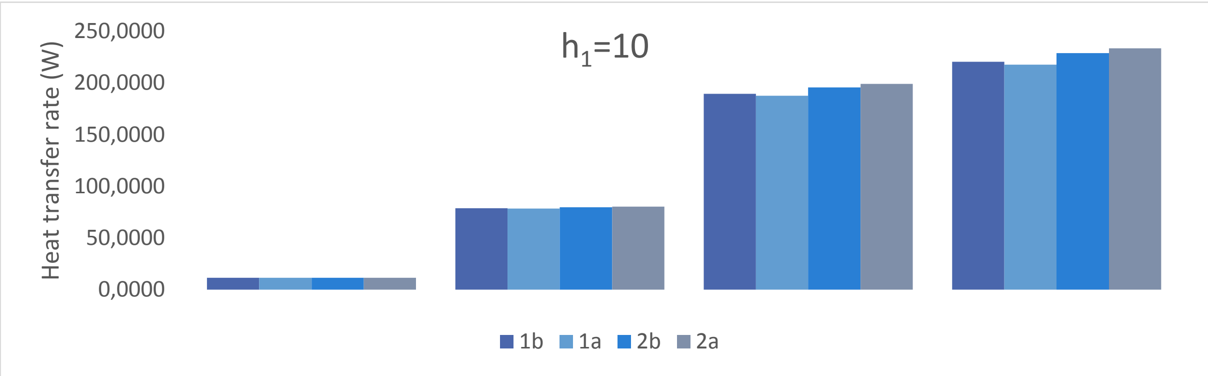
Parameter	Unit	Description	Value	Comments/Source
h_1	W/m^2.K	coefficient PE to mold	1/10/100/1000	Unknown
h_2	W/m^2.K	coefficient Mold to water	170	[22, 20]
R_1	m	Typical bottle radius	0,06	
R_3	m	Outer mold radius	0,07	R_1+t
H_1	m	Typical bottle height	0,20	
H_2	m	Height of mold	0,21	H_1+t
t	m	Mold wall thickness	0,01	Minimum recommended by suppliers: 6,5 – 10 mm
k	W/m.K	conduction coefficient	0,2	[22]

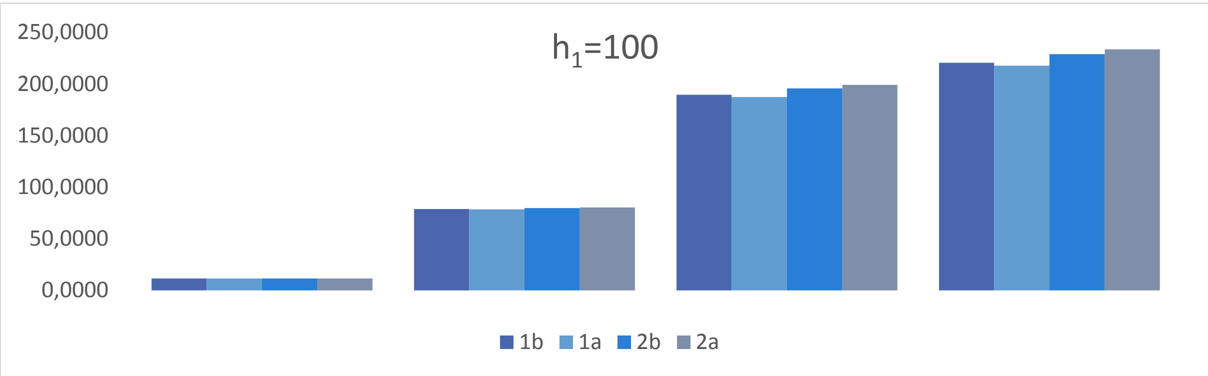
Four different situations are calculated:

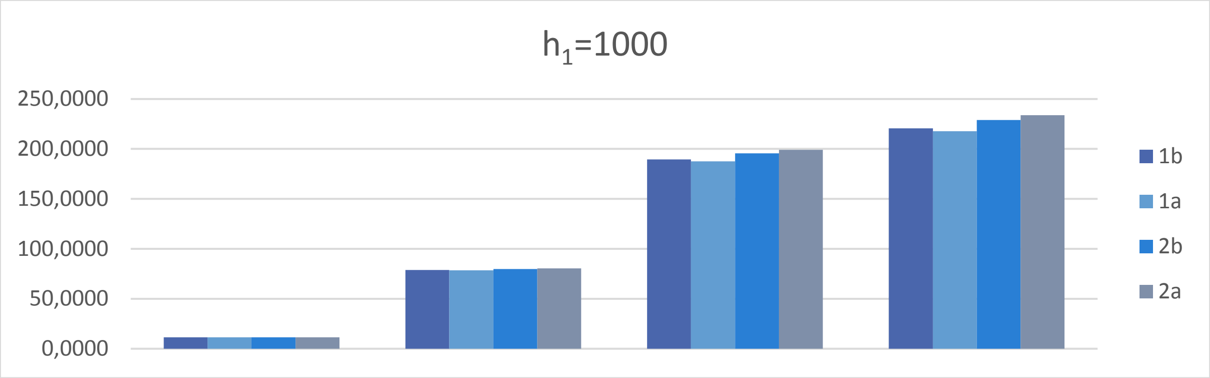
1. The mold is cooled on the outside by air.
    a. Normal flat outside surface
    b. The outer mold surface area is increased by putting raised ribs on it. This also implies that the mold wall thickness will be increased by 30% (see Figure 14).
2. The mold is cooled on the outside by water.
    a. Normal flat outside surface.
    b. The outer mold surface area is increased by putting raised ribs on it. This also implies that the mold wall thickness will be increased by 30% (see Figure 14).

In order to find out if assumption 4 is valid, different values for h_1 are used to find the comparison between the four situations. See the figures below:









As you can see, independent of the value for h_1 the comparison between the four situations remains in the order 1a<1b<2b<2a.

The increase from situations 1a to 2a ranges from 0,4-7%.

APPENDIX 2 – TIME REQUIRED TO HEAT UP THE MOLD

The heat flow coming into the mold is the internal heat of the blown PE. The heat flow through the entire mold is calculated according to:

Equation 4

$$Q = \rho . c_p . d . \left(\frac{T_0 + T_{mold}}{2} - T_{mold} \right) = \rho . c_p . d . \frac{T_0 - T_{mold}}{2}$$

Here the assumption is made that the temperature at the mold surface is an average between the polymer melt temperature and the mold temperature.

Table 8 - Parameters used in equations 6-8

Parameter	Unit	Description	Value	Comments/Source
d	m	distance from mold surface to cooling channel	0,01	equal to mold wall thickness
ρ	kg/m^3	density of mold material		
T_0	K	Temperature of polymer melt		
T_{mold}	K	Temperature of mold		
k	W/m.K	conduction coefficient		

Furthermore, the heat flux that can actually get into the mold due to thermal resistance of the mold material is:

Equation 5

$$Q = k \frac{T_0 - T_{mold}}{d}$$

Combining Equation 4 and Equation 5**Fehler! Verweisquelle konnte nicht gefunden werden.**, the time required to heat up the mold can be calculated to be:

Equation 6

$$\tau = \frac{\rho c_p}{k} . d^2 = \frac{1}{\alpha} . d^2$$

α represents the value of thermal diffusivity which is a parameter that can be found in literature for a lot of construction materials.

Table 9 - Thermal diffusivity of different materials [21, 22, 20, 23]

Material	Thermal diffusivity (mm^2/s)
ABS	0,12
PC	0,15
PE	0,11
Steel	8 - 67
Aluminum	97

From these we can make a comparison in times to heat up the mold: