

Sheet-metal based molds for low-pressure processing of thermoplastics

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Applying thin metal sheets for the manufacturing of thermoforming molds

ABSTRACT: Current mold technology, used in thermoforming processes such as vacuum forming, often lack in material and energy efficiency during their lifecycle. These molds, mostly milled out of solid blocks of aluminium, take long to produce and come at a high cost. Moreover the tempering of the vast mass of these molds requires more energy than that of sheet metal ones. These drawbacks result in a high cost of the formed product.

The goal of this research is the development and the technical and economical validation of faster producible, cheaper, and material and energy efficient molds based on plastically deformed metal sheets. Design guidelines have been developed to ensure that (a) appropriate sheet metal forming techniques can be used, (b) the required structural stiffness is obtained and (c) the desired thermal pattern can be achieved.

One technique in particular is considered to produce the deformed metal sheets, namely Single Point Incremental Forming (SPIF). This technique can produce generic, freeform shapes using a standard, spherical, CNC controlled tool and is characterized by its short lead times. The manufactured deformed metal plates are thin, resulting in very low thermal inertia and thus good thermal efficiency, but they cannot cope with the forces during the thermoforming process and must be supported.

1 INTRODUCTION

When producing small series of a plastic or composite product, the cost of the mold plays a significant role in the price setting and the time needed to produce a mold is often considered a real bottleneck. Low-pressure forming processes, such as thermoforming, rotational molding and resin transfer molding, use molds that typically have a complex and deep form, while the demands on mechanical stability are rather limited. There is a general demand for improved techniques to manufacture such molds, not only from the plastics- and composites processing industry, but also mold manufacturers desire to improve and diversify their technologies. The present paper focuses on a new type of molds that are based on 3D-shaped metal sheets, offering the perspective of cheaper and faster producible molds for thermoforming processes, in particular vacuum forming. Sheet metal forming techniques, such as spinning, are readily available, whereas more advanced techniques, such as SPIF (Single Point Incremental Forming), are still the subject of further development and thus not well known in industrial settings. Furthermore, several challenges that come with the use of sheet metal molds, such as

stability issues and temperature control systems, need to be overcome.

Thermoforming is the shaping of a plastic product starting from a polymer sheet. The sheet is first heated to a temperature range where it is easily deformable. Next, the sheet is stretched into or onto a cool mold. The sheet is then cooled to a temperature where it will retain the shape of the mold. Finally the formed part is removed from the mold and any excess material is trimmed from the part. Thermoforming is a taxonomy label for a vast group of processes, including vacuum forming, free bubble forming, mechanical bending, twin sheet forming, pressure forming, matched mold forming, drape forming, etc. Furthermore, a distinction is made between heavy-gauge (thick sheet) and light gauge (thin sheet) thermoforming. In vacuum forming the sheet is drawn against the mold surface by applying a vacuum. The differential pressure, caused by the vacuum, presses the sheet against the mold. (Throne 2008)

In the study underlying this paper the potential of sheet metal molds for thermoforming purposes in general and for vacuum forming in specific has been investigated.

Section 2 of the paper describes conventional molds in thermoforming, and their drawbacks and characterizations. Section 3 discusses the sheet metal molds, in particular the selection of an appropriate manufacturing process of the mold, its thermal and mechanical design and the overall benefits and drawbacks.

2 CONVENTIONAL MOLDS

2.1 *Mold requirements*

Molds used in vacuum forming are subjected to the following criteria:

- The mold must shape the plastic sheet accurately.
- The mold must be dimensionally stable.
- The mold must be able to remove heat from the plastic sheet.
- The mold must withstand the forming pressure of the vacuum and thermal stresses at elevated temperatures.
- The mold must withstand environmental conditions during storage.
- The mold surface may not adhere to the plastic sheet.
- The mold surface must be hard enough to resist wear.
- The mold must resist chemical attacks, such as from corrosive gasses of the plastic sheet. (Throne 1996)

2.2 *Mold materials*

There are two categories of thermoforming molds. The first are the production molds, typically made of aluminium. The second are the prototype molds. These can also be made of aluminium or of a more easily to process material, such as wood, fibreboard or thermoset plastic. Prototype molds are meant to produce a few parts or to test design concepts.

The focus of this paper is on aluminium production molds, because it is the most used material in vacuum forming. Aluminium is very well suited as mold material for several reasons: good wear resistance, good heat transfer characteristics, easy to machine, castable and lightweight.

2.3 *Mold making*

There are two commonly used methods for making a mold out of aluminium.

The first method is by casting the aluminium in a mold made out of foundry sand. Copper coolant channels can be cast into the mold. After casting, vent holes must be drilled in the vacuum forming mold and its surfaces must be finished.

The second and most used method is making the mold out of solid blocks of aluminium, with computer-aided milling machines. The advantage of this

method compared to casting is that the mold dimensions can be more accurate. Although this is the most common used method, there are still some disadvantages, which will subsequently be described.

During mold design and production some extra features need to be taken into account: cooling, venting, undercuts, mold surface texture, etc. When the mold is produced on a milling machine, the cooling/heating channels are often omitted, because of the effort and extra costs needed to drill them in the mold. (Bouffiioux & Henrard & Eyckens & Van Bael & Sol & Duflou & Habraken 2008)

2.4 *Disadvantages*

Machined aluminium molds typically are characterized by a high mass and take a long time to produce, adding up to a high labor and machine cost of the mold. Besides, a lot of aluminium is wasted during milling, especially for deep molds. This results in a high cost of the mold and of the final product in small batch production.

Most disadvantages which occur during the use of these molds are related to their large mass. This large mass (high thermal inertia) is thermally inefficient, because of the great amount of energy that is needed to reach the required mold temperature, leading to long startup times in production. Therefore, thermal cycling of the mold is hardly used in vacuum forming and a mold temperature is chosen as a compromise between the formability of the plastic sheet during forming and the form stability of the formed product after demolding.

Another drawback related to the mass is the labor effort it takes to change molds, because of their high weight.

Prototype molds are characterized by their short lifetime, caused by the inferior materials used to manufacture the mold.

In the next chapter sheet metal molds will be discussed as a solution to the problems of conventional molds, caused by their vast mass and the waste of aluminium.

3 SHEET METAL MOLDS

3.1 *Production*

Different techniques to form a sheet metal plate into a mold shape already exist. For example: roll forming, stretch forming, drawing, stamping, rubber forming, bending, cutting, hammering, blanking, piercing, spinning, shearing, hydroforming,... are all being used today. With these methods it becomes possible to produce molds faster and at a lower material cost. Depending on the geometry of the mold not all techniques can typically be used. New techniques like Two-Point Incremental Forming (TPIF) and Single-Point Incremental Forming (SPIF) are

the focus of ongoing research. These advanced techniques can produce generic, freeform shapes using a standard, spherical tipped, CNC controlled tool. Selection of the correct sheet metal processing technique is an important step in the development of the mold. Therefore, a software tool has been developed that selects the most suitable technique from a set of mold production technologies. This software tool is developed based on a decision flowchart developed with a taxonomy of mold features (prismatic, axisymmetric, freeform or ruled) and a set of add-on features, such as hole, slot, groove, pocket, chamfer, etc. that can be added to the mold, and a set of mold design parameters such as dimensions of the mold, mold material, etc. The set of mold production techniques available for selection are techniques that require minimal material to produce the mold, in contrast to casting the mold or milling it out of a solid block. Of these techniques, one of the most versatile and upcoming sheet metal prototyping technologies, SPIF, is discussed in detailed below.

3.2 SPIF

Single Point Incremental Forming (SPIF) is a sheet metal processing technique in which sheet metal is formed in a stepwise fashion by a CNC controlled tool, which follows a specific tool-path (Figure 1). In contrast with other forming processes, SPIF does not require a dedicated (partial) die to operate. This technique allows for a fast and cheap small batch production of sheet metal parts, shown in Figure 2. (Duflou & Verbert & Belkassem & Gu & Sol & Henrard & Habraken, 2008)

SPIF still has some severe limitations. The forming time to produce large part can take up to hours, due to its slow incremental nature, compared to conventional sheet metal processing techniques. Because of the elasticity of the material there is also spring-back, which can be compensated by adjusting the tool-path. The most used materials in SPIF are soft and easily deformable aluminium alloys that have low wear resistance. An important drawback is

the reduction of sheet thickness. The higher the wall angle of a part, the lower the resulting sheet thickness is. The latter is a major drawback when using parts created with SPIF as molds, because thin parts result in structural weakness. Equation (1) is an approximation of the resulting sheet thickness (t_f) after forming as a function of the original sheet thickness (t_0) and wall angle (α). This means that for certain materials, the formable wall angle is limited. (Henrard 2008)

$$t_f = t_0 \sin\left(\frac{\pi}{2} - \alpha\right) \quad (1)$$

SPIF can process different alloys such as aluminium, titanium, copper and steel. The materials used for the sheet metal molds were aluminium alloys AA3103 and AA1050 because of their good workability and thermal conductivity. AA3103 has proven to be well suited for SPIF with a maximum wall angle of 72° . (Henrard 2008)

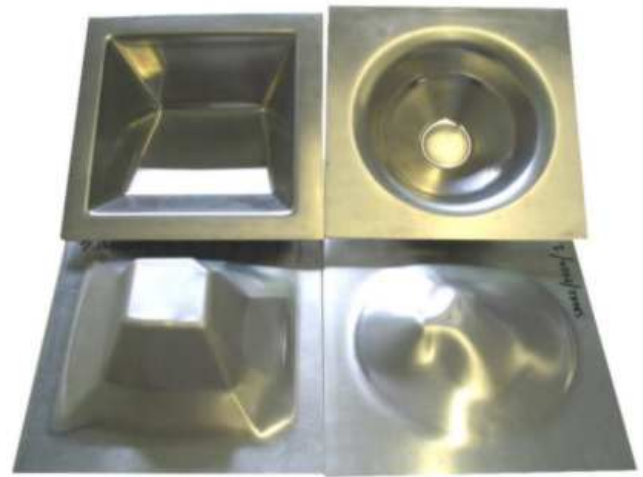


Figure 2: Parts created with SPIF

3.3 Mechanical design

One of the downsides of sheet metal molds is that the deflection of the mold under pressure must be taken into account. This is not the case for conventional solid aluminium molds. Therefore the me-

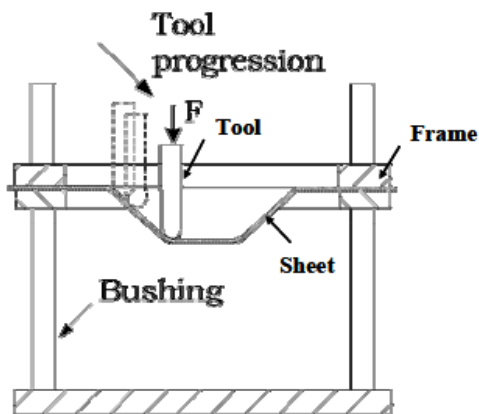


Figure 1: Single Ppoint Incremental Forming process, with example of cone. [3]



chanical design becomes an important element in the development of sheet metal molds. This is demonstrated in Figure 3. This figure shows a mold created with SPIF from an aluminium blank with a sheet thickness of 1.5mm (pyramid dimensions: base 142 mm x142 mm, angle 70°, height 80 mm). When this mold is put under vacuum pressure, the mold will immediately collapse. Thus the sheet metal mold itself is not sufficiently stable.

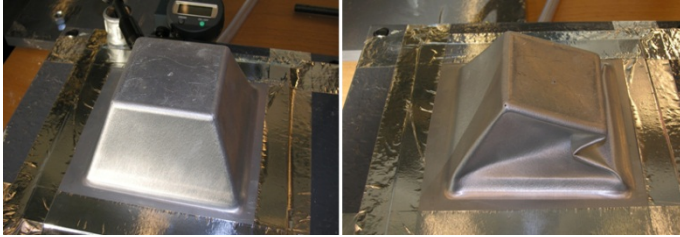


Figure 3: Pyramid mold under vacuum pressure.

Several solutions can be considered for this problem. The first one is to increase the thickness of the metal sheet. The thickness must be chosen so that the deflection is within the tolerances, when the mold is put under mechanical stress.

The necessary thickness can be determined by Finite Element Analysis (FEA) or by analytical formulas. It is advised to use FEA for molds with complex shapes. Figure 4 shows the maximum deflection of the mold in function of the sheet thickness, determined with the software Creo Simulate 1.0. It can be concluded that for the earlier described pyramid a thickness of more than 3.5mm would be needed as the starting thickness of the blank metal sheet.

The formulas used in this research are from Timoshenko (Timoshenk & Woinowsky-Krieger 1959). For simple molds these formulas are as accurate as the results from FEA. For more complex molds it is advised to use FEA. Following formulas (2, 3, 4, 5) can be used to approximately calculate the deflection of the pyramid mold (Figure 5). Depending on the geometry of the mold, other formulas from Timoshenko can be used to approximate the deflection. Timoshenko has described formulas for circles, ellipses, triangles and other geometric forms.

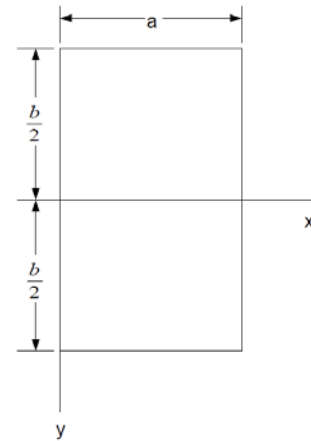


Figure 5: Representation of rectangle wall of a mold.

$$W = \frac{4 q a^4}{\pi^5 D} \sum_{m=1,3,5,\dots}^{\infty} \frac{1}{m^5} \left(1 - \frac{\alpha_m \tanh \alpha_m + 2}{2 \cosh \alpha_m} \cosh \frac{2 \alpha_m y}{b} + \frac{\alpha_m}{2 \cosh \alpha_m} \frac{2 y}{b} \sinh \frac{2 \alpha_m y}{b} \right) \sin \frac{m \pi x}{a} \quad (2)$$

$$W_{max} = \frac{5 q a^4}{384 D} - \frac{4 q a^4}{\pi^5 D} \sum_{m=1,3,5,\dots}^{\infty} \frac{(-1)^{\frac{m-1}{2}} \alpha_m \tanh \alpha_m + 2}{m^5 2 \cosh \alpha_m} \quad (3)$$

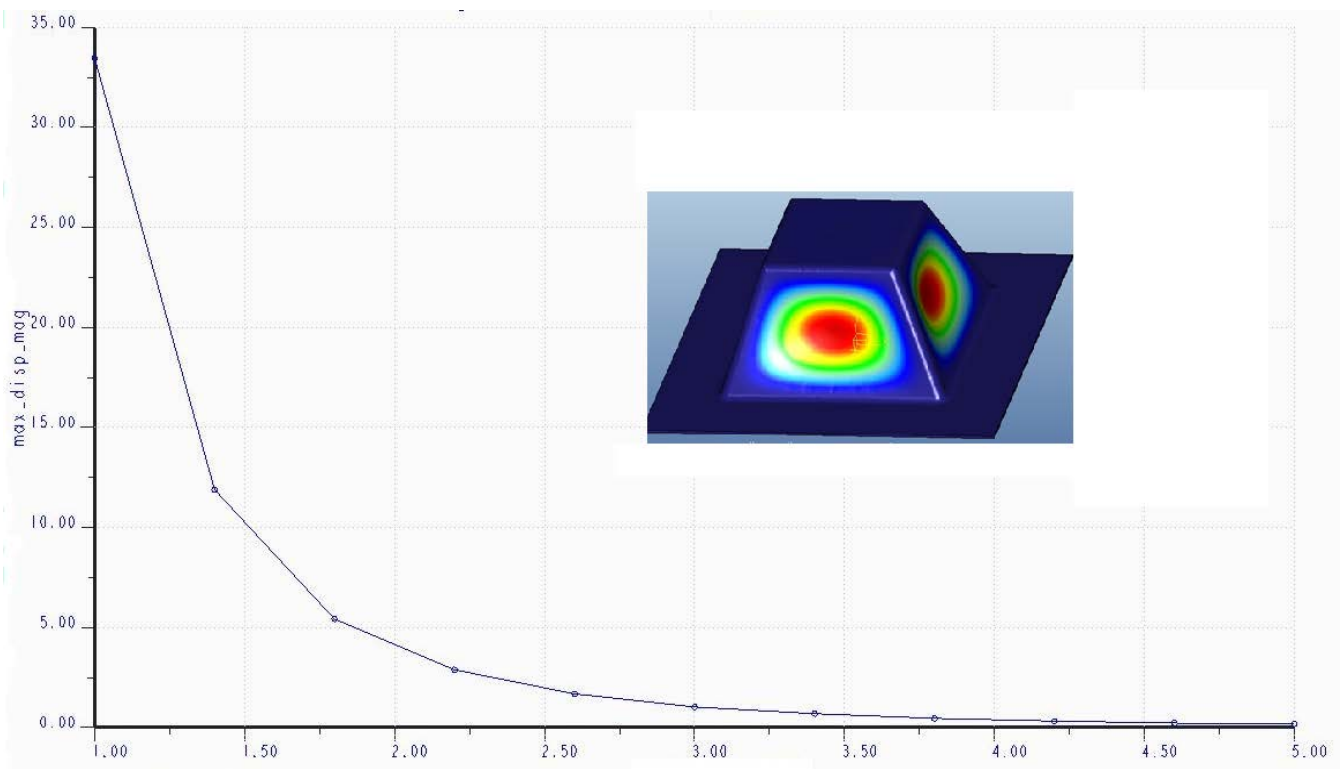


Figure 4: Maximum displacement (deflection) (mm) as a function of the original metal sheet thickness of a pyramid mold created with SPIF, submitted to vacuum pressure.

$$D = \frac{E h^3}{12(1-\nu^2)} \quad (4)$$

$$\alpha_m = \frac{m \pi b}{2 a} \quad (5)$$

w : the deflection of the side of the mold.

w_{max} : the maximum deflection of the side of the mold (at the center of the rectangular plate).

a, b : the length and the width of a rectangular side of the mold.

x, y : the x - and y -coordinates from the point of which the deflection must be calculated.

E : Young's modulus.

h : starting thickness of the metal sheet.

ν : Poisson's ratio.

The sheet thickness is a factor that determines which processes can be used to produce the mold. For example, current available SPIF infrastructure limits the sheet thickness to 2mm for soft aluminium alloys. This means that it is impossible to produce the pyramid mold with the available SPIF setups, because the maximum deflection during thermoforming will be bigger than 3mm.

Instead of using a thicker sheet, a second solution is to support the mold with a grid of points or lines. When designing these support structures, both the formulas of Timoshenko or FEA can again be used. A grid of points for example can be realized by using a discrete mold as described by Walczyk & Lakshminathan & Kirk (1998). This discrete mold can then serve as a support for the sheet metal mold.

A third solution is by globally supporting the sheet metal mold. The bulk that supports the mold can be manufactured in different ways. It can for example be milled out of cheaper materials such as wood or MDF. The bulk can also be poured in the form of the mold using, plaster, concrete, pouring (thermoset) resins. This last method is the most usable for vacuum forming, namely pouring a mixture that will form a porous rigid support at the back of the mold, which allows the air to escape through the supporting structure. In this case only holes need to be drilled in the sheet metal mold for evacuating the air. This method is demonstrated in the next example. Figure 6 shows a female mold created with SPIF. The overall dimensions of this part are 400 mm x 400 mm x 280 mm. Figure 7 shows the mold in a box made of MDF boards. This box serves to cast in the porous mixture and as a support for the sheet metal mold. Figure 8 shows the mold after casting in the porous mixture, with a close-up of the surface of the porous mixture.

The porous mixture consists of AR-8/16-340 and ALWA-MOULD D / ATLAS M 130 a casting resin. AR-8/16-34C are expanded clay grains with a diameter varying between 8 and 16 mm and a density of

333 kg/m³ which makes the mixture lightweight. AR-8/16-34C is produced and delivered by the company ARGEX. ALWA-MOULD D / ATLAS M 130 is a two component resin system based on methyl methacrylate. Aluminium powder can be added to the mixture as filler for the resin. After addition of the curing agent for the resin, the mixture sets quickly, forming a porous structure.

After the mixture has set and the necessary vacuum holes are drilled in the sheet metal, the mold can be used for vacuum forming. The porous structure allows air in the mold to escape quickly, resulting in a vacuum.

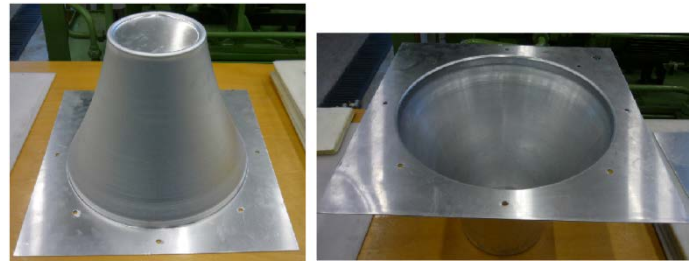


Figure 6: Female mold created with SPIF.



Figure 7: Mold in a box of MDF.



Figure 8: Porous mixture casted as a support structure.

3.4 Thermal efficiency

It is clear that a thin sheet metal mold has a greater thermal efficiency due to its smaller mass than an aluminium mold milled out a solid block. This enables thermal cycling during the vacuum forming process. Thermal cycling is nowadays almost never used due to the long switchover times and the great amount of energy needed to vary the temperature of a solid aluminium mold.

The thermal stability and energy efficiency should be considered in the choice of the support

structure. The thermal conductivity and heat capacity of the support structure (like in Figure 8) will influence these two factors. Most of the above suggested supports will have a negative influence to the thermal characteristics of the mold. The mixture of AR-8/16-34C and resin has a low thermal conductivity, which makes it harder to remove heat from the mold and to reach a uniform temperature over the surface of the mold. (Bens & Van Mieghem & Appermont & Vanhove & Van Bael & Duflou & Ivens 2012) On the other hand, this method of supporting has the benefit that heating elements can be placed very close to the sheet metal mold, before pouring the porous mixture.

4 CONCLUSION

Sheet metal molds can offer better use of material and better energy efficiency. It can be concluded that sheet metal molds are a valuable alternative for solid aluminium molds, in small production series. The greatest and most promising advantage of sheet metal molds is that they allow faster thermal cycling in the thermoforming process, although further research is needed.

When designing a sheet metal mold, the available production techniques and mechanical stability of the molds need to be taken into account. Depending on the geometry of the mold and sheet thickness a suitable technique can be selected. SPIF has been chosen to create experimental molds and has proven to be a suitable technique, with the downside that the metal sheets are too thin to create mechanical stable molds. The molds need to be supported to prevent unwanted deformation of the mold during thermoforming. A porous mixture of expanded clay grains and resin has been tested and has shown to give a good support.

When using other supports (or no support at all) it is important to choose a sufficient sheet thickness to make sure the deflection of the mold is within tolerances. To determine the necessary sheet thickness FEA or the formulas of Timoshenko can be used.

5 ACKNOWLEDGMENTS

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