MOLD DESIGN AND PRODUCTION BY USING ADDITIVE MANUFACTURING (AM) - PRESENT STATUS AND FUTURE PERSPECTIVES

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Abstract: *This paper covers the advanced Additive Manufacturing (AM) techniques applied to injection mold design and production. Its aim is to do a comprehensive analysis on what AM is doing for the recent and future perspectives in the field of mold's production.*

Further analyses are done on the possible use of Rapid Tooling (RT) techniques based on AM technologies. These include plastic mold inserts made using high strength polymer resins and metal-based technologies for direct tooling work.

Moreover, the work also reviews conformal cooling channel design based on laser sintering AM technologies and its effect in improving mold cooling efficiency to reduce cycle times, which is an important issue in the injection molding process.

Finally, a brief techno-economical analysis is presented, as well as a comparison between the two different types of molds – the conventional ones, and molds produced by rapid tooling. The conclusions leads toward future usage of RT and AM in the mold design and production.

Keywords: injection molding, additive manufacturing, 3d printing, rapid tooling, stereolithography, laser sintering

1. Introduction

Injection molding as a manufacturing process has always been a challenge because the tooling design is always specific for each part. This means that toolmakers have to use a variety of manufacturing technologies in order to produce a tool with a precise shape, correct feeding and cooling channels and easy ejection.

With the rise of additive manufacturing technologies in the last decade, a lot of the limitations in conventional manufacturing have been circumvented. Additive manufacturing uses layer-by-layer fabrication of three-dimensional physical models directly from a computer-aided design (CAD) model. AM takes the virtual design from a CAD or some other 3D modeling software, transforms it into thin, horizontal cross-section layers and then stacks those layers together in physical space, one after another until the physical model is completed. When this process is used to produce physical prototypes and models for various applications it is referred to as Rapid Prototyping (RP). When AM technologies are used to directly manufacture tools or tooling inserts for injection molding or for any other technology that requires a specific shape to produce a part, then the process is called Rapid Tooling (RT).

Rapid Tooling involves all AM procedures that lead to final parts used as cores, cavities, or inserts for tools, dies and molds. Two sub-levels must be distinguished: direct tooling and prototype tooling (Fig. 1.1).

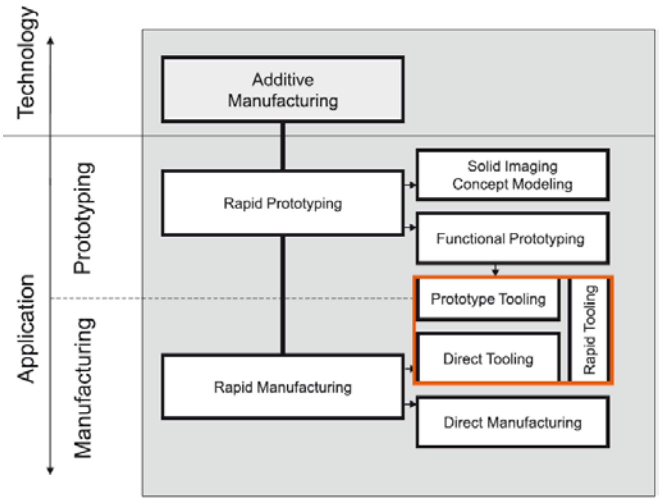


Fig. 1.1 *AM: rapid tooling, defined as a subcategory that integrates prototype tooling and direct tooling (Source: [4])*

Direct Tooling is technically equivalent to Direct Manufacturing but leads to tool inserts, dies and molds (Fig. 1) in series quality. It is important to understand that "Direct Tooling" does not mean that the entire tool is made by AM, in fact only tool components, such as cavities or sliders, are generated. The entire tool is made using these cavities and standard components or inserts within a traditional tool making process.

Prototype Tooling is used when a mold in series quality often is too time and money consuming for small series manufacturing. If just a few parts are needed or details are changed frequently, a temporary mold made from substitute material is typically sufficient. This kind of mold shows the quality of functional prototypes but meets, at least partially, the direct tooling application level.

The primary advantage of RP and RT is its ability to create almost any shape or geometric features, even those complex shapes that would be virtually impossible to machine. With additive fabrication, the machine reads in data from a CAD model and lays down successive layers of different materials, and builds up the physical model from a series of layers. Those layers are joined together or fused automatically to create the final shape matching the CAD model.

2. Rapid tooling technologies

Currently, there are several AM technologies that can be used for rapid tooling purposes. This paper will focus on two: Selective Laser Melting (SLM) and Stereolithography (SLA).

Selective Laser Melting (SLM)

SLM machines (Fig. 2.1) consist of a build chamber to be filled with powder with a grain size of up to 50 μm and a laser scanner unit on top that generates the x -y contour. chamber is designed as a movable piston that can be adjusted at any z-level. The top of the powder bed defines the build area in which the actual layer is built. The whole build chamber is preheated to minimize laser power and completely flooded by shielding gas to prevent oxidation. The laser beam contours each layer. The contour data are obtained from the slice data of each layer and directed by the scanner. Where the beam touches the surface, the powder particles are locally molten. The geometry of the melting spot is defined by the laser beam diameter and the traveling speed. While the beam travels further, the molten material solidifies by thermal conductivity into the surrounding powder. Finally, a solid layer is achieved. After solidification of one layer, the piston at the bottom is lowered by the amount of one layer thickness, thus lowering the whole powder cake including the semi-finished part. The emerging space on the top of the powder is filled with new powder taken from the adjacent powder feed chamber using a roller. The roller rotates counter-clock wise to its linear movement in order to spread the powder uniformly. This procedure is called recoating.

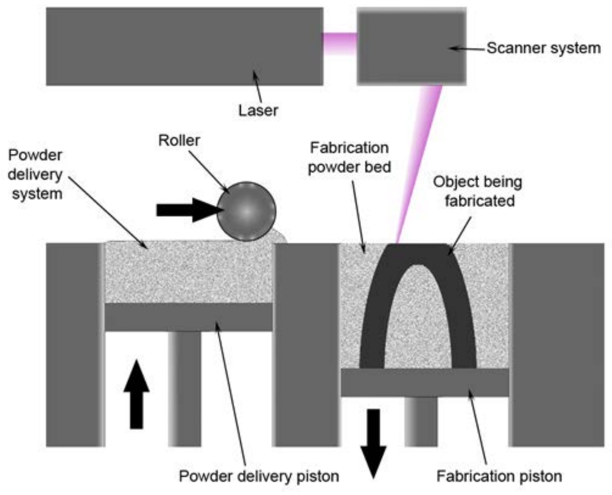


Fig.2.1 *Selective Laser Melting (SLM) – Schematic (Source:cadimensions.com)*

After recoating, the build process starts again and processes the next layer. The whole process continues layer by layer until the part is completed. In most cases, the top layer is made using a different scan strategy in order to improve its solidity. After the build is finished and the top layer is processed, the whole part, including the surrounding powder, is covered by some layers of powder. This so-called powder cake has to be cooled down before the part can be taken off by removing the part from the surrounding powder. The cool-down can be done in the machine; however cooling down in a separate chamber allows immediate beginning of a new build job.

The process is generally called selective laser melting, (SLM) but depending of the machine manufacturer, the process can be called differently (ex. EOS-GmbH has patented the DMLS technology). It was developed in particular to process metal parts that need to be very (> 99%) dense, and is used to manufacture injection molding inserts for larger production series, that have a specific geometry difficult to manufacture with conventional means. Since the parts manufactured by SLM have a high density and isotropic mechanical characteristic they can be used as Direct Tooling inserts.

Fig.2.2. *Golf Ball blow-mold Left: Conformal cooling Right: Direct Tool cavity (Source: https://www.eos.info)*

This approach can potentially reduce the number of steps in the process and potentially impact overall part accuracy. The limitation in additive fabrication of tooling tends to be the required post-processing to achieve the required surface finish. Some processes like DMLS (EOS) and Laser Consolidation (Accufusion) have good raw finishing results, but typically mold inserts require additional polishing [4].

Selective Laser Melting (SLM)

A laser stereolithography machine consists of a build chamber filled with the liquid build material and a laser scanner unit mounted on top of it which generates the x-y contour. The build chamber is equipped with a build platform fixed on an elevator-like device that can be moved in the build (z -)direction. On this platform the part is built. The laser beam simultaneously does the contouring and the solidification of each layer as well as the bonding to the preceding layer. The motion of the beam is controlled by the slice data of each layer and directed by the scanner.

If the curable build material is applied by print heads, the process is called polymer printing or polymer jetting. It can be regarded as a 3D printing process; however, due to the part building by UV curing of liquid monomers it is a polymerization or stereolithography process. The build material is directly applied to the build platform through a multi-nozzle piezo-electric print head. The solidification is done simultaneously by a twin light curtain. It is created by two synchronously traveling high performance UV lamps. The layer thickness is only 0.016 mm, which creates very smooth surfaces. Adjacent layers are processed by moving the platform in the z-direction. The process continues layer by layer until the part is finished. The parts need supports during the build process. The supports are generated automatically and build simultaneously by a second set of nozzles so that each layer consists either of build or of support material. Consequently, the supports are solid and consume a large amount of material. The support material can be washed out without leaving marks in a mostly automated post process.

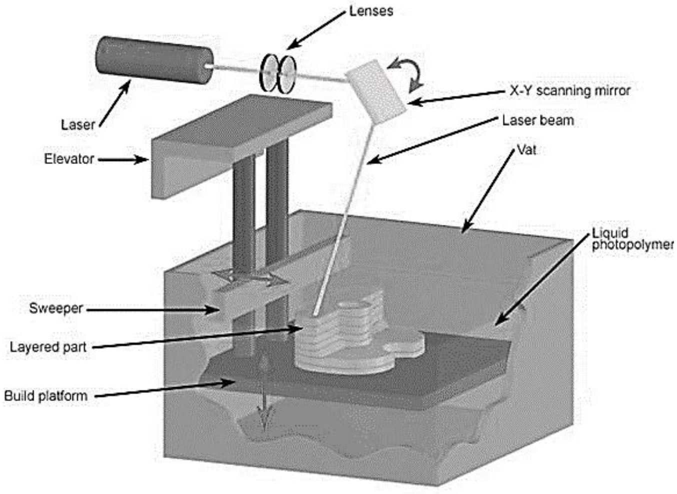


Fig.2.3. *Stereolithography (SLA) – Schematic (Source:http://www.custompartnet.com)*

By using stereolithography based AM like the Stratasys patented PolyJet 3D printing (Fig. 2.3) we can manufacture prototype tooling to validate the performance of the plastic parts. This is a viable production technique for short runs and smaller series, but since the material properties of the mold resin require different processing parameters (molding temperature, injection pressure, packing time etc.) currently SLA is used mostly to assess the parts functionality. This is possible because the prototype tooling can be finished in 2 to 3 days. Conventional tooling on the other hand, can take up to few months to manufacture.

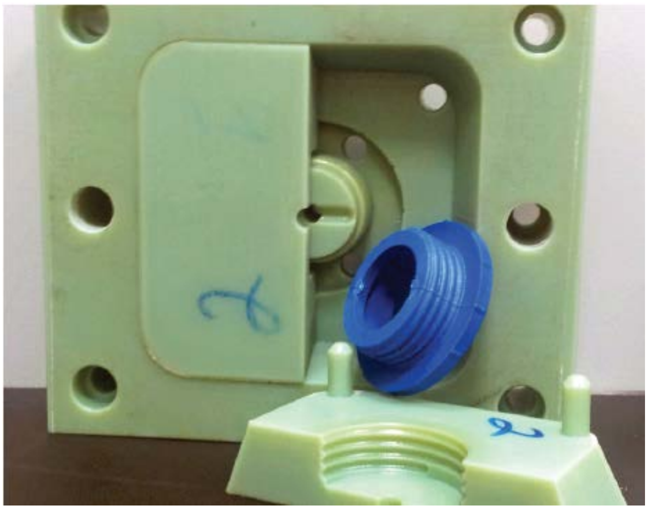


Fig.2.3. Three-piece mold made with PolyJet Digital ABS material (Source: Stratasys.com)

3. Conformal cooling

Since the inception of industrial injection molding, keeping an even temperature on the surface of the mold has been a constant challenge. Optimal cooling reduces cycle times by a significant amount since it often takes more than 50% of the entire cycle time.

The cooling system is extremely important to the economics and operation of the designed mold, and yet remains one of the most under engineered systems in injection molds. Perhaps the reason for the lack of engineering is that the temperature distribution is not that obvious when molding compared to flow related defects.

Improperly designed cooling systems often result in two undesirable outcomes. Firstly, cooling and cycle times are much longer than what could have been achieved. Secondly, significant temperature gradients arise across the mold, causing differential shrinkage and warpage of the moldings. To operate effectively, cooling systems must be carefully designed to manage the heat flow throughout the mold without incurring undue cost or complexity.

When optimizing mold cooling there are 4 basic principles:

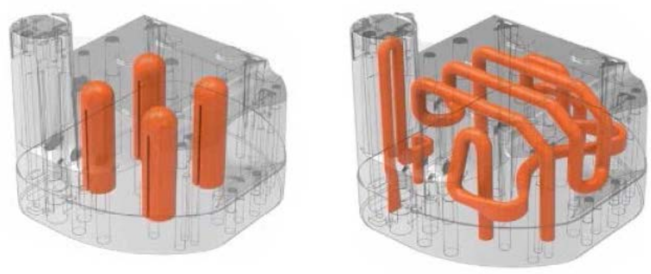
1. Wall thickness. Cooling time increases exponentially with the wall thickness of the part. With 1mm walls, many materials cool in five seconds. At 5 mm, cooling times extend from 40 to 75 seconds.

2. Thermal diffusivity. This ratio of thermal conductivity to heat capacity is important because the lower the thermal diffusivity of the material, the longer it will take to extract heat from molten plastic.

3. Mold temperature. Higher mold temperatures help reduce pressure during the filling phase and improve surface finish, but they can double or triple cooling time.

4. Depth and pitch. The size, depth, and spacing of cooling channels should result in temperature differences across the mold surface of no more than 5°C for semi-crystalline materials and 10°C for amorphous materials. More channels spaced closer together near the surface of the mold accelerate cooling while maintaining surface temperature uniformity.

In their quest to maintain even temperatures, manufacturers have used baffles, bubblers and heat pipes; they've laminated blocks together and added complex drilling set ups to their molds. Over the last decade, conformal cooling has been proposed as a solution for controlling injection molding temperatures. Mold inserts can be built with internal cooling channels that follow the contour of the cavity beneath the surface (Fig. 3.1, b). Because the shaping of the cooling channels follows the contour of the mold, the method is called conformal cooling. Due to the increased heat extraction, the productivity of a plastic injection mold can be increased significantly. In addition, cooling and heating channels can be designed to obtain an integrated heat management system and thus much more effective tools.



a) b)

***Fig. 3.1** Conventional cooling channel core with bufflers (a) vs. conformal cooling channel design (b) (Source: 3dsystems.com)*

In recent years, a lot of case studies have been done proving the effectiveness of cooling channels for parts with complex geometry. One of those studies featured by 3DSystems with is for a core with a tapered helix that is positioned on the inside of a spacing cone used for industrial assemblies (Fig 3.2). Conformal cooling channels were created by rotating a teardrop configuration so that one side was parallel to the outer surface of the core while maintaining a constant distance from it. By running the cross-section along a tapered helix, Bastech was able to design geometry that the ProX DMP 200 could build in a single run.

***Fig. 3.2** A Bastech mold core insert with conformal cooling channels prototyped using 3D Systems' Stereolithography (SLA) technology and printed in maraging steel on the ProX® DMP 200. (Source: 3dsystems.com)*

As expected, the conformal cooling mold maintained a lower temperature throughout the run and reduced cycle time by 14%. This design can also be applied to molds made by materials other than metals, but as it stands now, metal based AM technologies are still the standard when it comes to designing conformal channels for larger production series molds.

***Table 3.1:** Baffled vs. Conformal Core – Cycle time [3dsystems.com].*

	Conventional	Conformal	Savings
Mold Temp	44 ^{o}C	44 ^{o}C	
Cooling	10.5 sec.	7.5 sec.	
Cycle Time	35 sec.	30 sec.	5 sec./part

Table 3.2: *Baffled vs. Conformal Core (Source: 3dsystems.com).*

	Start Up	20 shots	40 shots	60 shots		
	Mold Temp °C	Mold Temp °C	Mold Temp °C	Mold Temp °C	Flow [l/min]	Cycle time [s]
Baffle core	29	37	39,5	38,2	5.3	58
Conv. Cavity	28	28,3	28,7	26,8	5.3	58

	Start Up	20 shots	40 shots	60 shots		
	Mold Temp °C	Mold Temp °C	Mold Temp °C	Mold Temp °C	Flow [l/min]	Cycle time [s]
Baffle core	29	33,67	33	32.5	5.7	45
Conv. Cavity	28	30	29,67	29,67	5.7	45

Cooling channel surface area of baffled core = 1561 cm²
Cooling channel surface area of conformal core = 3368 cm²

The use of conformal cooling channels optimizes the molding process by providing a constant temperature gradient throughout the mold all the while increasing the total surface area of the cooling circuit. This also results in savings in manufacturing the inserts.

Table 3.2: *Baffled vs. Conformal Core – Cost savings [3dsystems.com].*

	Conventional	Conformal	Savings
Design	30	7	$1,495.00
Programming	40	17	$1,495.00
Machining	74	56	$990.00
Material/ AM Build	$350.00	$5,400.00	-$5,050.00
EDM	72	0	$3,960.00
Polishing	38	45	-$385.00
		Total	$2,505.00 [16%]

However, conformal cooling adds new layers of design and production complexity to the moldmaking process, placing it beyond the means of most shops. The investment in AM machines is not always justified, especially when manufacturing simpler injection molded parts. In those cases, the use of conformal cooling is not needed and conventional channels manufactured with drilling can be used to get similar results.

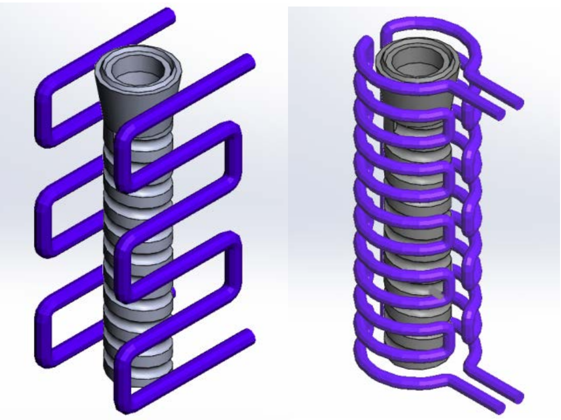


Fig. 3.3 *Conventional cooling channel (a) vs. conformal cooling channel design (b) for a plastic part with simple geometry*

A simple FEA analysis of the part shown in Fig. 3.3 with constant coolant flow and mold temperatures showed that the conformal cooling design only improves the cooling time less than 5%

4. Conclusion

3D printing is commonly used to build prototype parts for the detection of issues related to form, fit and function. Yet, 3D printed prototypes cannot provide a complete assessment of an injection molded part's functional performance because 3D material properties are different than those actually used in injection molding. AM technologies based on SLA can replace soft, aluminum tools that, until recently, were the only option for manufacturers to conduct design and functional testing of injection molded products.

Currently, metal based AM processes are the only viable technologies for large series of injection moldings, At this point conformal cooling channels are the main reason why AM inserts are used in injection molding tools, however the use of the tooling inserts made by laser sintering techniques can be further extended to manufacture specific geometries of the mold that are more prone to wear and have to be replaced after a specific number of runs.

Injection mold tooling made with composite SL resins is viable for use in short-run injection molding, allowing for the production of hundreds of parts. With fine control of process parameters, the process repeatability should be acceptable for the majority of small-to-medium-sized parts.

Finally, the anisotropy in dimensional accuracy as well as the thermal management of AM tooling and dimensional accuracy of the cavity and core are some issues that have to be addressed in order to maximise tool life and part quality.

5. References

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