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White Paper

Conformal Cooling

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Introduction

Injection molding is a process by which plastic pellets are melted and then forced into a mold, where the material forms its final shape. Once the cavity is filled, coolant disperses through cooling lanes within the mold in order to bring parts down to an appropriate dispensing temperature. According to Khan et al. (2014), part cooling is an important part of the process to produce quality parts but consumes 50% to 80% of the cycle time per build. Conventional cooling paths are machined in straight lines. A coolant flows through the channels at a given temperature and pressure, optimizing cycle time and part quality. This method produces flawed results because straight paths cannot provide consistent cooling throughout the mold cavity. Cooling rates for a given mold segment depends, in part, on its proximity to cooling channels. Non-uniform cooling across parts leads to longer cycle times, uneven cooling, warpage, and scrap.

What is Conformal Cooling?

Conformal cooling is a promising alternative with growing acceptance. Cooling channels follow with the part's contours to facilitate faster and more uniform cooling. Until recently this simple concept has been difficult to execute. Some of the geometries required in conformal cooling are impossible with traditional machining. The emergence of additive manufacturing (AM) has increased the availability of conformal cooling to mold designers. Using direct metal laser sintering (DMLS) or other additive manufacturing techniques, complex cooling channels can be optimized during the mold design phase rather than post-processed at suboptimal locations.

Methods

DMLS is the most prominent AM technique for manufacturing conformal cooling molds. There are several other techniques outside of additive manufacturing being employed including vacuum diffusion bonding and liquid interface diffusion. Based on information from Huang et al. (2013), and Die Bond, a mold manufacturer, both of these methods build the conformal cooling channels by machining complex grooves into a series of layers then fusing them together ("Die Bond," n.d.).

According to Huang et al. (2013), a patent for vacuum diffusion bonding was written in 2002 documenting the capabilities for conformal cooling but little research has been conducted since. Several articles have indicated that this type of technology is less expensive than DMLS but the method has not caught on as quickly as DMLS. Several companies are manufacturing mold inserts using technologies similar to vacuum diffusion bonding; however, several existing patents have forced many of those businesses to invent their own method for bonding. Hickerman and Helper (2013) identify that the additive manufacturing cost-per-mold is greater than it is for other methods due to the high cost for powdered metal. DMLS is still attractive to mold manufacturers because it is more accessible, multifunctional, and better-known than the competing technologies.

Benefits

Conformal cooling channels allow the coolant to access all part locations uniformly, making the cooling process efficient and consistent. It is not always possible to reach all part areas with conventional methods. Depending on how much of the volume is inaccessible, the cycle time can increase significantly. Reviewed journal articles specify that conformal cooling cycle time reductions range from 15%, Guilong et al. (2010), to 50%, Hsu et al. (2013). Case studies and news articles document similar savings; Fuges (2012) reported cycle time reductions in the 15% to 45% range and a case study by Fado, a mold manufacturer, stated a 60% savings ("Offer Case Study 2," n.d.). Improvement levels depend on many factors, including part geometry, conformal cooling design, and cooling channel parameters. For example, Hickerman and Helper (2013) indicate that with no engineering effort the cycle time savings is roughly 10% using conformal cooling. That number ranges between 20% and 40% after engineering analysis. With a more in-depth review, mold designers can optimize channel sizes and locations as well as the coolant temperature and pressure. As discussed later, mold designs can be split up into regions by proximity and peak temperature. This allows engineers to generate parameters that benefit each localized area instead of proposing sub-optimal, uniform values across the whole mold.

Conformal cooling also reduces scrap rates; this is in part due to the reduction in the temperature variation across the part. For example, in a Fado case study, one conformal cooling design resulted in a 70°C reduction in temperature variation and a 97% reduction (1.6% to 0.05%) in scrap ("Offer Case Study 3," n.d.). Efficient cooling achieved by conformal cooling prevents the overall part from reaching as high temperatures as with conventional cooling channels; this helps reduce the cycle time and the amount of part shrinkage.

Improvements in scrap and cycle time only mean so much if direct metal laser sintered conformal cooling molds have a tool life significantly less than conventionally made molds. Several trade articles, including Mayer (2005), indicate that conformal cooling molds can withstand roughly one million injection molding cycles, the same number of cycles as conventionally manufactured molds ("Injection," n.d.). Research has been conducted to validate their equivalence; however, there have not been many journal publications on the subject. Stwora and Skrabalak (2013) were able to confirm the claim by demonstrating that there is no compression strength, density, or hardness performance differences between molds made from conventional methods and additive manufacturing.

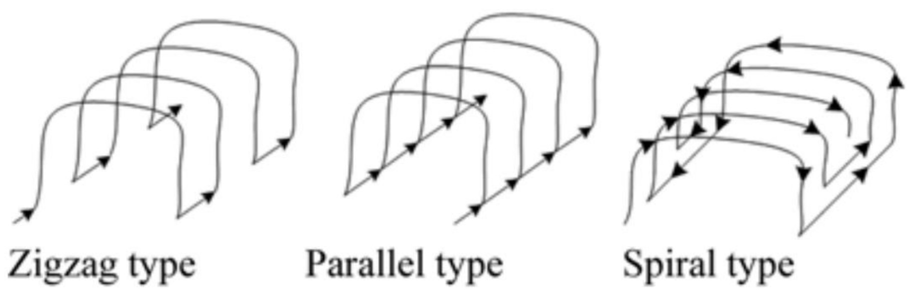

Figure 1 – There are three main coolant flow strategies for conformal cooling channels, zigzag (series), parallel, and spiral (Park and Pham, 2009).

Design for Conformal Cooling

According to Park and Pham (2009), there are three different techniques to be employed when designing conformal cooling channels: zigzag, parallel, and spiral; see Figure 1. Depending on the geometry of a part, these methods may be used in combination or on their own. The zigzag pattern, also known as a series cooling path, has part regions cooled one after the other rather than at the same time. Cooling in series is generally not preferred unless parts are small enough that the delay is negligible. The parallel channel design allows for different areas of the mold to be cooled at the same time. Park and Pham (2009) acknowledged that the main drawback for the parallel cooling method is that it requires a lot of coolant. The spiral conformal cooling channel design is often used with parts that have curvature or spherical elements. When designing conformal cooling channels, Park and Pham (2009) recommend using an injection molding software package in order to identify temperature zones within a mold so that the conformal cooling channels can be separated and optimized within each region instead of across the whole part.

Wall thickness of molded product (in mm)	Hole diameter (in mm) b	Centerline distance between holes a	Distance between center of holes and cavity c
0 - 2	4 - 8	2 - 3 x b	1.5 – 2 x b
2 - 4	8 - 12	2 - 3 x b	1.5 – 2 x b
4 - 6	12 - 14	2 - 3 x b	1.5 – 2 x b

Figure 2 – Channel size (b), distance to the next channel (a), and distance to the wall cavity (c) are all related to the part wall thickness and proportional to each other (Mayer, 2005).

The EOS whitepaper by Mayer (2005) is often cited when describing the design guidelines for conformal cooling channel diameter and location. The author, however, notes that the recommendations are no different than they were for conventional cooling practices. Because conformal cooling opens up design capabilities, those channel guidelines become more relevant. As shown in Figure 2, the hole diameter (b), centerline distance between holes (a) and distance from the centerline to the cavity (c) are proportional to each other and related to the mold wall thickness.

Conformal cooling channels manufactured through DMLS or other AM technology have some design limitations. For example, the smaller and longer the channels are, the more difficult it is to remove the support powder material after the print job has completed. According to Xu et al. (2001), there are four factors at play which define the feasibility region for length and diameter of the cooling channels: coolant pressure and temperature variations, ability to remove support material, and the actual part geometry. In general, Mayer (2005) recommends that the channel diameter should range between 4 and 12 mm, but that may have to change based on the other parameters described above.

Another limitation to using DMLS is the size restriction. Print beds for laser sintering machines typically run between 250x250x325 mm for the EOSINT M 280 and 500x500x500 mm for the 3DSystems ProX 400. Given the current cost for some powdered metals as well mold size constraint, there is still room for other conformal cooling technologies to support the industry’s needs.

Driving Forces of Conformal Cooling

Although the concept of conformal cooling has been around for at least a decade, momentum is finally starting to build. As Augustin Niavas from EOS stated in an interview with European Tool and Mould Making, the tool and die manufacturers are still learning about the technology and are waiting to see where the industry goes (“Interview,” 2014). Unless these manufacturers already own 3D printers it is a significant investment to enter into manufacturing molds with conformal cooling channels. Companies that either manufacture or provide 3D printing services are currently the main drivers for conformal cooling. They recognize the potential gains for the tooling industry and see their printers as the means for obtaining those savings.

Fraunhofer, in Germany, is one of the research organizations also investigating the potential of conformal cooling. According to a press release from November 2014, the organization was the first to bring conformal cooling to the EuroMold trade fair in 2014 (“Cost-effective”, 2014). Additionally, under Horizon 2020 by the European Union, which funds research projects throughout the region, a project called Intelligent and Customized Tooling (IC2) investigated new and more efficient tooling methods. The project contained finds about the benefits of conformal cooling but was not exclusively about that technology (“Community,” 2014).

Barriers to Adoption

The adoption of conformal cooling has barriers similar to other new technologies: high upfront investment costs (i.e., new molds or equipment), distrust in the technology, and a hesitation to learn a new design strategy. That being said, visibility and acceptance is growing through journal publications and case studies. Research is being conducted to demonstrate that parts manufactured using AM are no worse than ones using subtractive methods. Conformal cooling acceptance will also grow with the maturity of additive manufacturing. As material costs go down and the sizes of print beds go up, the attraction to conformal cooling DMLS molds will likely increase.

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