Additive Manufacturing Applications for the Tooling Industry:

Custom Conformal Cooling for Injection Molding

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As a combination service bureau specializing in additive manufacturing, rapid tooling and the reselling of additive manufacturing equipment, Bastech has had the opportunity to develop conformal cooled cavities and cores for years. Unfortunately, the metals printing process at the time was laborious in post processing and did not yield a 100% steel or aluminum parts that the tooling industry would widely accept. The development of 3D printing in 100% metal with reasonably smooth surfaces and realistic post processing is providing a rock solid tool to the molding and mold-making industry. This paper is intended to show this community the advantages of conformal cooling as well as the side benefits to tooling production with additive manufacturing.

Designers have tried to achieve even temperature control on the molding surface ever since the beginning of injection molding. The use of baffles, bubblers and heat pipes are simply a few ways we have come close. Inserts made of more highly conductive material which laminate pieces of blocks together and incorporate many complex drilling set-ups start to show the extent mold-makers have gone through to evenly and quickly cool (or heat) the tools.

Conformal cooling in injection molding is simply defining thermal control channels that maintain a consistent distance from the part surface. These channels may become smaller in cross-section than typical drilled lines, but will be closer to the part surface and consequently closer together. The only way to manufacture cavities and cores of this nature is to utilize additive manufacturing or laminate many sections together with o-ring seals which can be problematic and show witness lines.

Several items need to be considered as we start designing conformal cooling. The first is the cross-sectional shape and the intended orientation in which the cavity or core will be printed. One of the known facts in building direct metal parts is that walls equal to or greater than 45 degrees to the build plate can be self-supporting. In some cases, this angle can go as small as 35 degrees. We also have to maintain a relationship between flow and length to make certain that we are not heating our coolant to a point that it is not effective in the last section of the run. This being said, many will design conformal channels simply by offsetting and trimming part surfaces to generate the thermal control channels.

A more simplistic method is to define a cross-section and sweep down control curves. For the sake of argument, let's define some cross-sections that may be used based on common cross-sectional areas that can relate back to common flow rates.

Circular cross-sections provide the least surface to flow ratio.
Perimeter = 1.374 in.

Squares provide slightly better surface ratio, but flat top is problematic to build.
Perimeter = 1.474 in.

Rotate the square or simply let the shape twist to achieve better build characteristics.
Perimeter = 1.474 in.

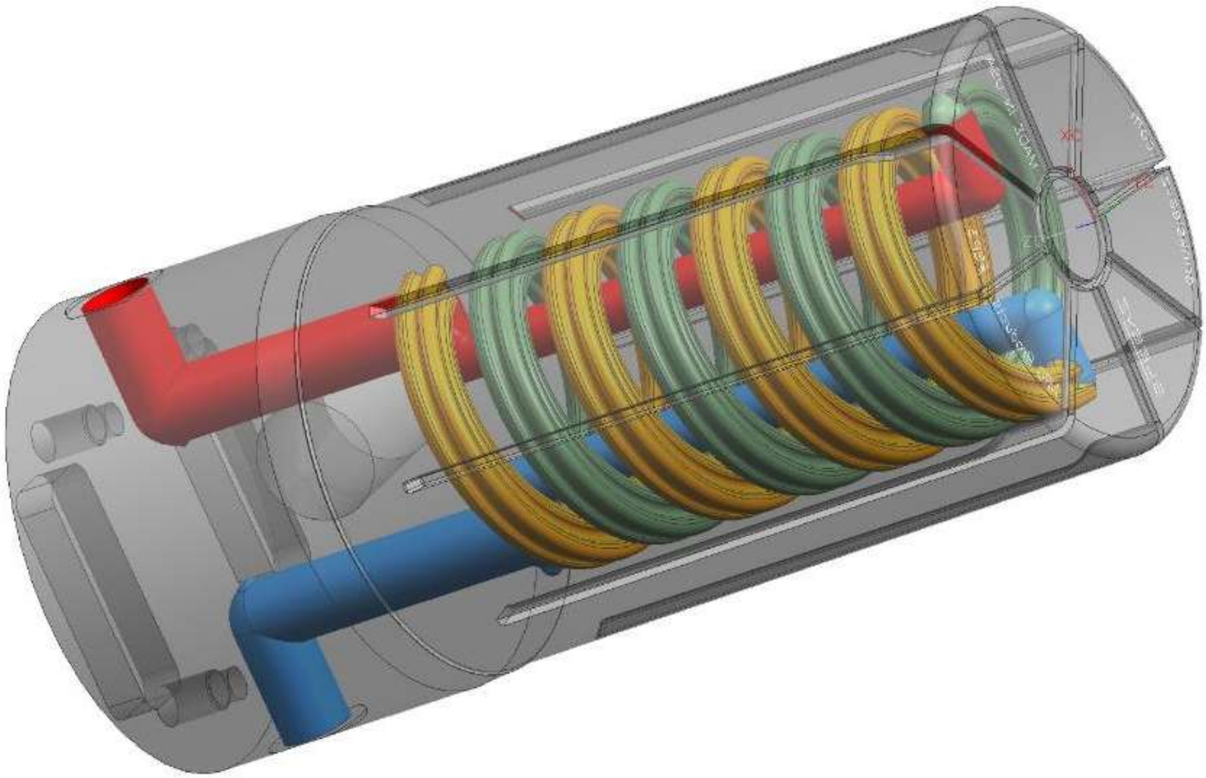
Triangular sections provide even better surface ratio and, with slight rotations, can provide accentuated conformal surface area.
Perimeter = 1.587 in. (16% increase)

Tear Drop cross-sections provide excellent build characteristics and reasonable conformal surface. However, the surface to flow ratio is not any better than the modified square.
Perimeter = 1.454 in.

By rotating the tear drop, we can achieve greater conformity to the part surface without reducing flow, surface area or build capability.
Perimeter = 1.454

Triangular sections, with a large radius opposite the conformal face provide excellent build characteristics, better surface ratio and can provide accentuated conformal surface area.
Perimeter = 1.574 in.

Another item to consider is breaking down the channel into a primary supply and return with multiple capillaries in-between. These capillaries can be smaller in cross-section and reach into smaller, more confined areas. In order to obtain good flow without risk of air pockets (dead zones) we need to make certain that the cross-section of the supply channel is equal to or greater than the sum of the cross-sections of the capillaries. In turn, we also need to make certain that the cross-section of the return line is equal to or less than the sum of the cross-sections of the capillaries. See image below.



The image above is an example of a reverse flow helix. The supply side is shown in blue and splits into two helical channels. One (green) starts from the base and works to the end of the core while the other (yellow) starts at the end of the core and flows to the base of the insert. In this case, the channels were designed to precisely split the cross-sectional area of the supply (and return) in half to maintain flow without dead pockets.

The designer also needs to be considerate of the ratio between the cross-sectional area and the length of channel. A cooling channel that becomes too hot toward the end of the run is simply unable to cool the tool and results in less than satisfactory results. While I am certain this ratio can be calculated, it is dependent on the volume of flow, the relative distance to the mold surface (heat source) and the desired thermal change (Injection temp. of material – desired mold temp.).

The advancements made in additive manufacturing are now driving some changes in CAD software. Cimatron is just one of these packages that is focusing on producing tools for the designer to implement conformal cooling. In addition, Moldex is working to make cooling simulation a reliable tool that the designer can verify the thermal capabilities prior to physical creation.

In an effort to put conformal cooling to the test, Bastech has taken two parts with comparable volume, size and design configuration and defined a conformal core to run in one of the molds, while the other is run with a standard spiral baffle configuration.

Bastech makes several versions of this core with a 3/8” NPT baffle running up the center. The most recent style brought the opportunity to manufacture the core with AM (maraging steel) and conformal cooling.

Advantages

- ***Speed***
  - Designed for AM, 2 days
  - Built on ProX 200, 3 days (with other parts)
  - Eliminated EDM all together
  - Minimized CNC machine time
  - Eliminated drilling procedures
- ***Molding***
  - Reduced core temp significantly
  - Reduced cycle time by 22%

The conformal cooling channels were simply created by rotating a teardrop configuration so that one side was parallel to the outer surface of the core and maintained a constant distance while trying to maintain the flow volume on the existing cores. By running the cross-section along a tapered helix, we were able to maintain an effective configuration with simple geometry on a single run.

	Start Up	20 shots	40 shots	60 shots		
	Mold Temp	Mold Temp	Mold Temp	Mold Temp	Flow GPM	Cycle time
Baffle core	84°F	98.9°F	103.1°F	100.7°F	1.4	58 sec
Conv. Cavity	83°F	83.6°F	83.7°F	80.3°F	1.4	58 sec

	Start Up	20 shots	40 shots	60 shots		
	Mold Temp	Mold Temp	Mold Temp	Mold Temp	Flow GPM	Cycle time
Conformal core	84°F	92.6°F	91.4°F	90.5°F	1.5	45 sec
Conv. Cavity	83°F	86°F	85.4°F	85.4°F	1.5	45 sec

The spreadsheet above shows the temperature differences in the mold halves of the two configurations. It becomes easy to see that the conformal core is staying consistently 10 degrees cooler than the baffled core, while providing a 13 second reduction in cycle time. One of the contributing factors to this drop in core temperature is an increase in the functional surface area of the conformal channel.

Cooling channel surface area of baffled core = 24.2 in^2
Cooling channel surface area of conformal core = 52.2 in^2

One item to note is that the only change between these two molds was in the core. The next iteration will include a conformal cavity along with the conformal core where we anticipate seeing even more significant reductions in cycle time as well as additional benefits in warp control.

In summary, the change in producing this core with additive manufacturing proved to be beneficial to both the mold-maker and the molder.

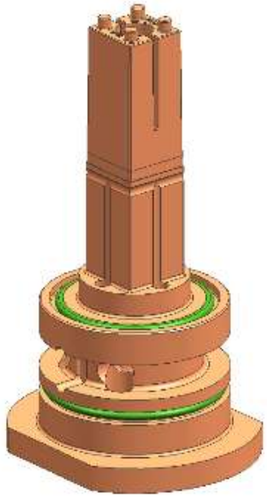
Benefits to mold maker:

1. Eliminated EDM work.
2. Prevented bottleneck on CNC machines.
3. Only fit surfaces were CNC machined, all others were simply polished.
4. 38 hour build (if by itself) eliminated 42+ hours of programming and machine time.

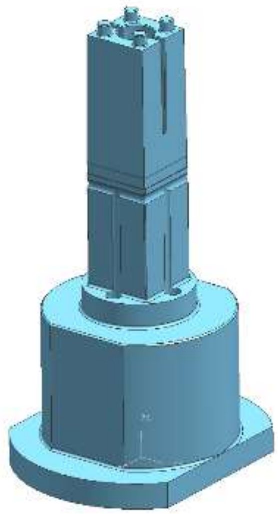
Benefits to Molder:

1. Tool was completed ahead of schedule.
2. 22% reduction in cycle time.
3. Conformal cooling was only done in the core. Conformal cooling in the cavity on the next tool should show even further improvement in warpage as well.

In an effort to drive the point home even further, Cimatron and Moldex 3D software have published (and are permitting Bastech to share) a conformal study that was done in conjunction with Lego. The tooling to mold the building blocks are quite intricate in an effort to minimize cycle time and maximize quality and consistency. A study was done using three different core configurations. The first was a standard steel core with a simple o-ring sealed channel around the base of the core. The second was produced out of steel with additive manufacturing and conformal cooling. The third core was manufactured out of Ampco Bronze with the same cooling as the first, conventional steel core.



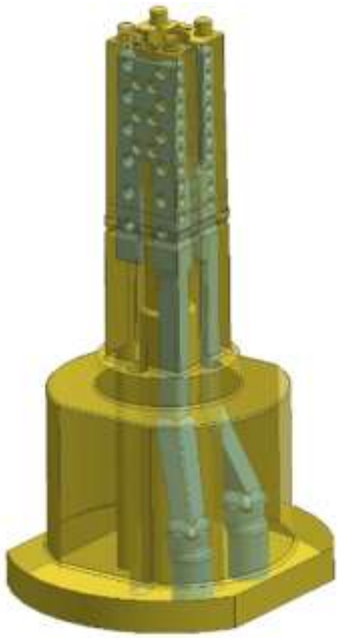
Conventional Steel



DMP Steel Conformal Cooled

Conventional Ampco

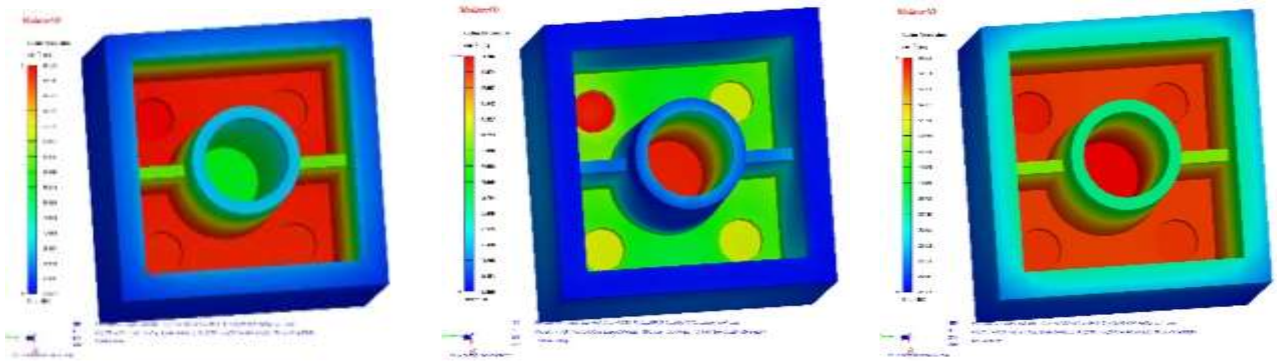
	Steel	**DMP**	**Ampco**
Conductivity:	$3\cdot10^{6}$ erg/sec·cm·K	$2\cdot10^{6}$ erg/sec·cm·K	$20\cdot10^{6}$ erg/sec·cm·K
Density:	7,75 g/cm^{3}	8 g/cm^{3}	8,7 g/cm^{3}
Heat Capacity:	$4{,}6\cdot10^{6}$ erg/g·K	$4{,}6\cdot10^{6}$ erg/g·K	$2{,}6\cdot10^{6}$ erg/g·K



The image to the left shows the core in a translucent state so as to see the cooling channels. It is important to note that the primary channel is created by simply offsetting the core surfaces and then adding connector bosses for strength.

The image at the right is simply to show the cooling channel prior to subtraction from the core.

While understanding how the conformal cooling was developed is important, the critical results are truly in the molding. This particular study showed a reduction in cycle time with significantly reduced temperatures at end of cooling.



	Conventional Steel	DMP Steel Conformal Cooled	Conventional Ampco
Cycle Time	23.2 Sec.	13.1 Sec.	13.1 Sec.
Temperature Range	20-95°C	20-51°C	21-62°C

In the molding industry (mold-making included), cycle time and accurate products are essential components to the bottom line. Additive manufacturing with conformal cooling can assist in minimizing warpage and certainly, as shown by these examples, reduce cycle time in the range of 22 to 45%. Answering the question: **Are we there yet? With an emphatic: YES!**