COOLING CONFIGURATIONS FOR RAPID TOOLING
"A Comparison Study"

Vito Gervasi, Christopher J. Urban, Steven E. Gerritsma

Rapid Prototyping Center
Milwaukee School of Engineering

Abstract

With advances in solid freeform fabrication and rapid tooling methods, true conformal cooling is becoming more feasible each year. As conformal cooling becomes more commonplace, methods for comparing cooling configurations are increasingly necessary. Milwaukee School of Engineering has developed a "simulated core-cavity" which was used to compare various cooling methods. The simulated core-cavity combines many features one might find in typical molds. In addition to developing a simulated core cavity, we have also developed a test fixture for collecting heat-removal-rate information. Heat removal rate information was gathered from difficult to cool locations on each simulated core-cavity. Several cooling configurations were tested, including conformal cooling and traditional cooling. Conclusions and recommendations for the use of conformal cooling with various tooling materials will be presented.

Introduction

"Conformal cooling" is used here to describe a system of cooling channels and openings – inline with or equidistant from– the surface of an object to be cooled. The cooling channels direct a fluid in a controlled manner, receiving heat from the surface which is then carried away from the system. Conformal cooling has several objectives aimed at improving the effectiveness of heat transfer from the object surface, through a material, and to the cooling fluid. One objective of conformal cooling is to bring the cooling channels as close as possible to the heated surface while maintaining structural integrity and tolerances. Another objective is to maximize the channel surface area through which heat may be transferred. A third objective is to induce turbulence for enhanced convection cooling, within the cooling channel. In many applications conformal cooling must remove heat in a uniform controlled manner; therefore controlling channel size and placement become critical objectives. In other applications, such as cooling objects with low thermal conductivity, the objective becomes the removal of as much heat as quickly as possible.

For many years the primary obstacle for the integration of conformal cooling into structures has been synthesis techniques. With traditional manufacturing, material is typically removed from a large billet, making it difficult and expensive to add internal features such as cooling channels. One approach is to machine multiple pieces which are assembled into a conformally cooled object. Near-net castings with expendable cores molded-in-place to form conformal cooling is another approach used by industry, with limited success, limited by channel size and length. A new approach, overcoming limitations of traditional manufacturing, is Solid Freeform Fabrication (SFF).

Unlike traditional material removal fabrication techniques, such as CNC machining, SFF is an additive process, starting with a void, and adding material one layer at a time to create a 3D object. CAD data is used to define the surface and interior of the solid 3D object, making complex part geometries as well as complex internal structures possible and commonplace. No expensive patterns, molds, or parting-lines are required when using SFF directly, making it a widely accepted, accelerated prototyping process.

The ability to create detailed complex conformal cooling systems with SFF is advancing each year. Powder based SFF approaches such as Selective Laser Sintering (SLS™, Rapid Steel 2.0 Metal™)[1] or 3D printing™ (Pro-metal™)[2] are capable of producing complex channels. The current limitation of these powder-based processes is the difficulty of removing powder from channels in a green body state without damaging the object. To minimize this difficulty, channels are made with wider diameters and shorter lengths, significantly reducing the effectiveness of the cooling system in some applications. With improvements in green strength, cooling channels will undoubtedly become longer and more complex. Another technique is to directly or indirectly create an expendable ceramic core, which is molded into a near-net-shape casting and later removed. SFF processes continue to advance, making very complex objects with intricate conformal cooling systems. With the known benefits of conformal cooling[3,4] for heat removal and the continual evolution of SFF technologies, a study was conducted to compare the effectiveness of several cooling systems.

Background

The Rapid Prototyping Center at the Milwaukee School of Engineering has been developing a new composite based epoxy matrix rapid tooling methodology for several years. With epoxy being a poor thermal conductor, improved heat removal was important. Current techniques for producing conformal cooling within cast RT tooling such as formed copper tubing or gun-drilled holes, seemed inferior to the potential of fine, contoured cooling channels.

The conformal cooling technique developed uses an expendable core, molded in place within the tooling material. Many geometries are possible including serpentine, zig-zag, straight-line, TetraLattice[5] and others. The expendable cores are first generated using CAD and later produced using SFF. The SFF can be used directly to form the channels or indirectly as an expendable-core mold. In the final stage, the expendable core is placed accurately within the mold face and cast in place. After the tool is cured, the expendable core material is removed, forming the conformal cooling channels.

Although this paper focuses on cooling systems comparisons, the thrust of this investigation was to develop a method for producing conformal cooling within RT. The goal for the conformal cooling configuration design was to bring the tightly spaced channels as close to the surface as possible, while maintaining structural integrity needed for injection molding.

Objectives

The first objective was to compare several standard RT cooling systems against a conformal cooling system. The second objective was to compare these systems under similar conditions using a standard pump and standard plumbing to gain a better understanding of the benefits of conformal cooling. The final objective was to form the conformal cooling channels as close to the surface as possible while still maintaining adequate wall thickness for injection molding pressures.

Methodology

To compare four cooling configurations an experimental tool called a "Simulated Core-Cavity" was developed and analyzed in a test apparatus. The following pages will describe the simulated core cavity, the four cooling configurations, as well as the test apparatus.

Simulated Core Cavity

The simulated core-cavity was designed to mimic characteristics of both the core and cavity halves of a typical injection mold. A shape was sought, which had irregular curves, sharp and rounded edges, as well as primitive recessed and protruding features. After considering a number of possible geometries the simulated core-cavity shown in figure 1 resulted. This design uses a 3D face scan with complex, difficult to machine, features. One half of the face is protruding from the theoretical parting line, and the other half is recessed into the simulated core-cavity. There are also two cylindrical shapes, with draft, one protruding and one recessed. The simulated core-cavity has indentations for snap-fitting into the test apparatus.

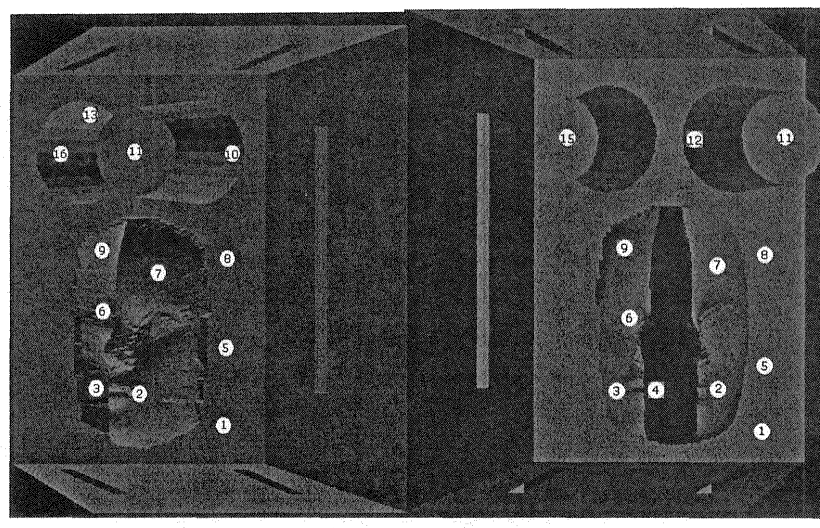

Figure 1. Simulated Core-Cavity with Data 16 Collection Points Displayed

To create the simulated core-cavities a silicone mold was used. Silicone walls were approximately 2 inches thick and reinforced with 1/4 inch aluminum rods *-to reduce mold deflection.* Simulated core-cavities were cast using standard aluminum filled epoxy. Cooling systems were cast-in-place or machined after casting *-depending on cooling type.* All simulated core-cavities were cast and post cured following a standard schedule and temperatures. Brass tubes were added to union with coolant pumping systems. Brass tubes were coated with silicone to minimize heat transfer to surroundings.

Cooling Configurations (figure 2)

No-Cooling

One option in RT is to not use any coolant channels, relying upon air cooling. This option is represented in the first simulated core-cavity which used no coolant channels.

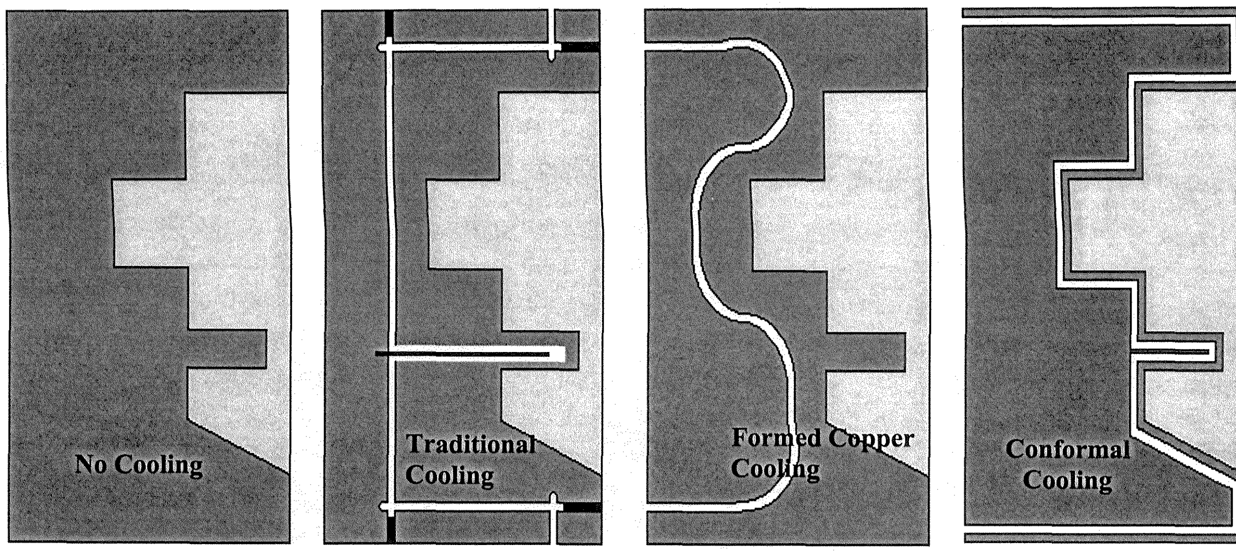

Figure 2. Cooling Configurations

Traditional Cooling

In some RT processes, such as DTM's RapidSteel2[TM,1] or 3D System's KelTool[TM,6], it is desirable to add a coolant channel network after the mold is created. For this traditionally-cooled simulated core-cavity, a network of interconnected drilled holes was capped off to direct coolant throughout the object. In addition to drilled channels, a baffle was used on one tall narrow feature.

Formed Copper Cooling

Many RT processes, such as AIM or composite tooling, use formed copper tubing to improve heat removal rates. Two cast-in-place methods can be employed for this type of cooling. The first method is a plumbed coolant system with elbows and tees soldered together, forming a near conformal cooling system. The second method (used for this study) uses formed copper tubing, bent to contour within the cooled surface. In both cases the copper is molded-in-place. To achieve maximum coverage on this simulated core cavity two formed copper tubes were used.

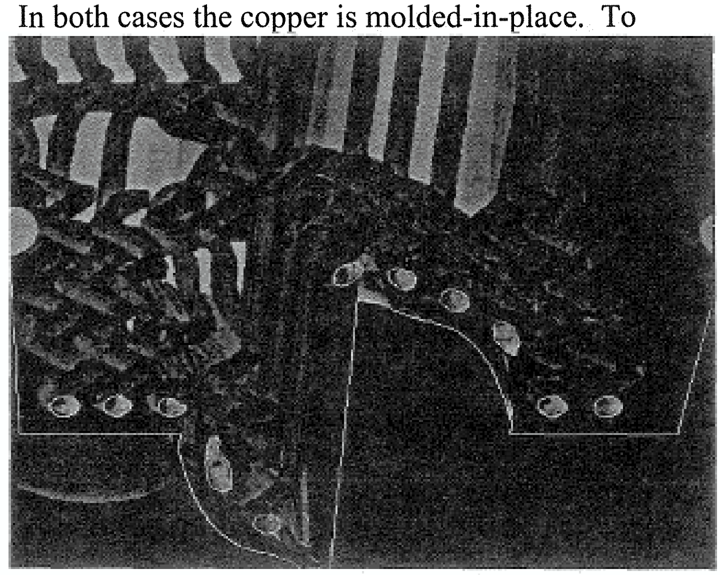

Figure 3. Zig-Zag Conformal Cooling Channels

Zig-Zag Conformal Cooling

Conformal cooling is the ideal coolant system for injection molding applications. As fine channels get closer to the cooled surface the ability to cool small, detailed features becomes more feasible. A simulated core-cavity with eleven 2.5 mm diameter channels, conforming to the surface in a zig-zag pattern was formed (figure 3). The channels were spaced 5 mm between centers at the minimum and 2.5 mm from the surface throughout. Channel spacing increased as surfaces became more vertical as a result of CAD modeling methodology.

Test Apparatus

A method was developed to test and record the heat removal rate at multiple points on the simulated core-cavity surface. To measure the heat removal rate at the same location on all simulated core-cavities an apparatus was created, with 16 test cells located at specific surface positions.

Figure 4 illustrates the basic design of the 16 test cells. The liquid volume of the cell, labeled pseudo-part, represents a plastic part. To measure heat transfer from the cell liquid to the simulated core-cavity coolant, a thermocouple and data acquisition system were used. Figure 5 illustrates the entire test apparatus.

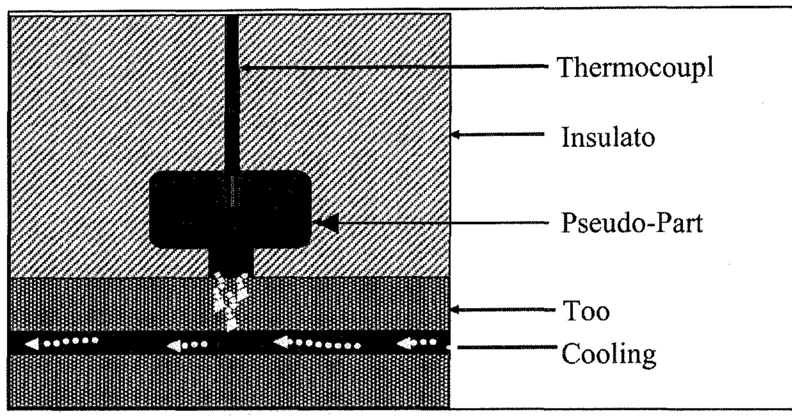

Figure 4. Test Cell Design

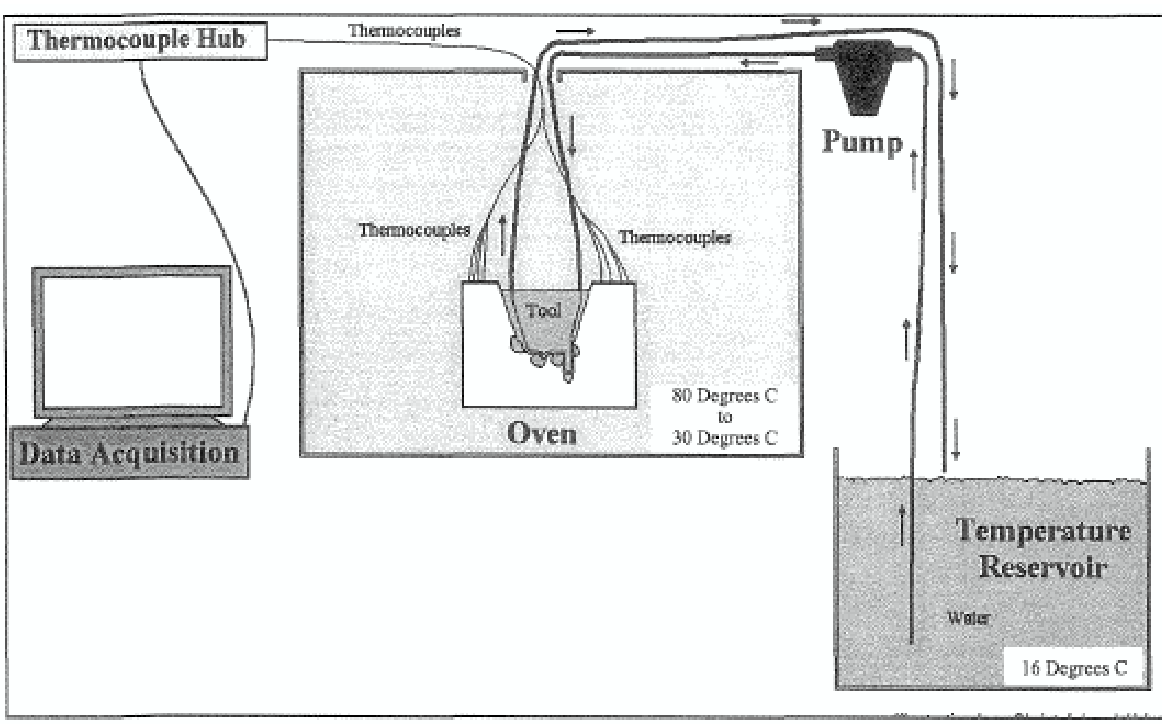

Figure 5. Complete Test Apparatus

To run the test, the simulated core-cavity was placed in the test apparatus and the test cells were filled with glycerol under vacuum. The coolant pump was connected to the simulated core-cavity, and the thermal couples were placed. The test cells and simulated core-cavity were heated to 80° C in a convection oven. To initiate the test the oven temperature setting was reduced to 30° C, the coolant pump was activated, and data collection began. When the temperature of all test cells fell below 45° C the test was stopped and data was analyzed.

Results/Discussion

All four simulated core-cavities were tested under similar conditions to determine the rate of heat removal for each system. The results were verified by testing the zig-zag conformal cooling system and the traditional cooling system a second time. The resulting data points were analyzed and used to generate three charts illustrated and discussed in the following pages.

Figure 6 illustrates an overall cooling configuration comparison. Performance of all four simulated core cavities is shown. Each line shown is an average of all 16 data points for each configuration. The slope of the curves for each configuration represents the rate of heat removal. The line for "no cooling channels" has a gradual slope with a relatively slow rate of heat removal. The traditional and copper tubing performed similarly to each other and significantly better than a lack of cooling channels. The conformal cooling has a steep curve, cooling the cells noticeably faster than traditional and copper tubing.

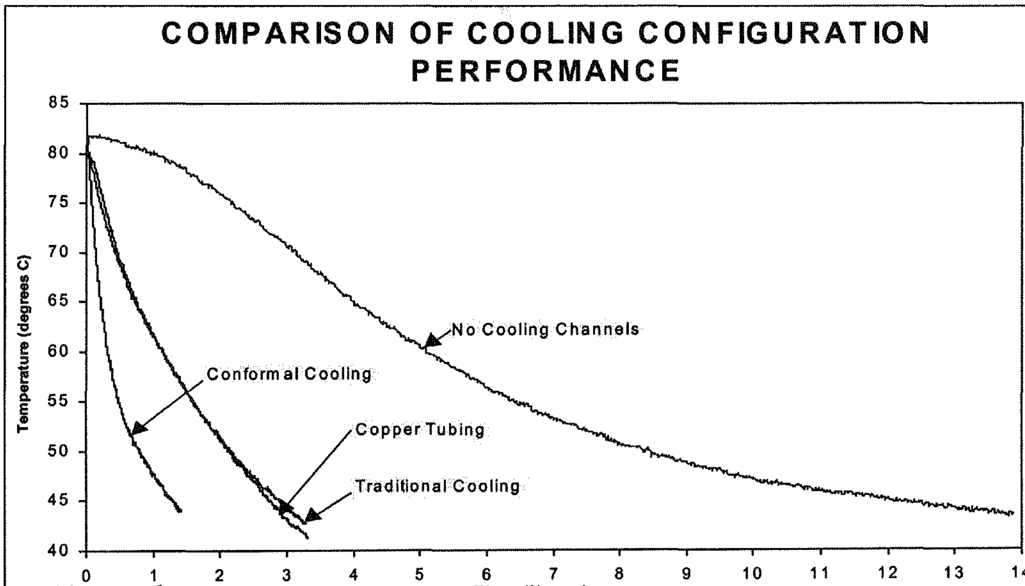

Figure 6.

Figure 7 illustrates the heat removal rates of each cooling configuration over a temperature range. No cooling has a relatively low heat removal rate. The traditional cooling has a comparable heat removal rate to that of the copper tubing: both rates are about three times that of no cooling. Conformal cooling has a heat removal rate about three times higher than the copper and traditional cooling. Therefore, conformal cooling also has a heat removal rate 9 times higher than no cooling.

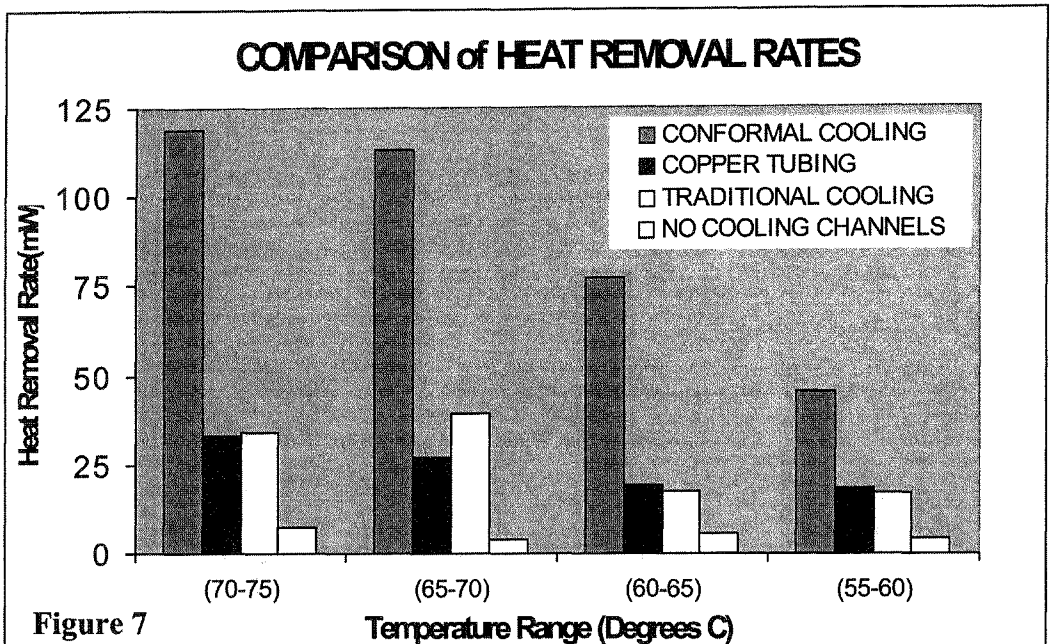

Figure 7

As SFF expands material capabilities it becomes of interest to predict how these materials may perform in conformally cooled injection molding applications. This portion of the paper will attempt to give some material performance insight into, not only current SFF materials, but also SFF materials of the future. The material used for this study was aluminum filled epoxy with a thermal conductivity of 0.8 W/(M*K). The heat removal rates of figure 7 were averaged to obtain one heat removal rate for each cooling system. These average heat removal rates for the aluminum filled epoxy were used to theoretically estimate the heat removal rate of other materials. To do this, thermal conductivity (K) for Stereolithography epoxy, ceramic filled epoxy, tool steel, aluminum, and copper were substituted in place of the thermal conductivity of aluminum filled epoxy. As shown in figure 8, stereolithography materials are considerably more

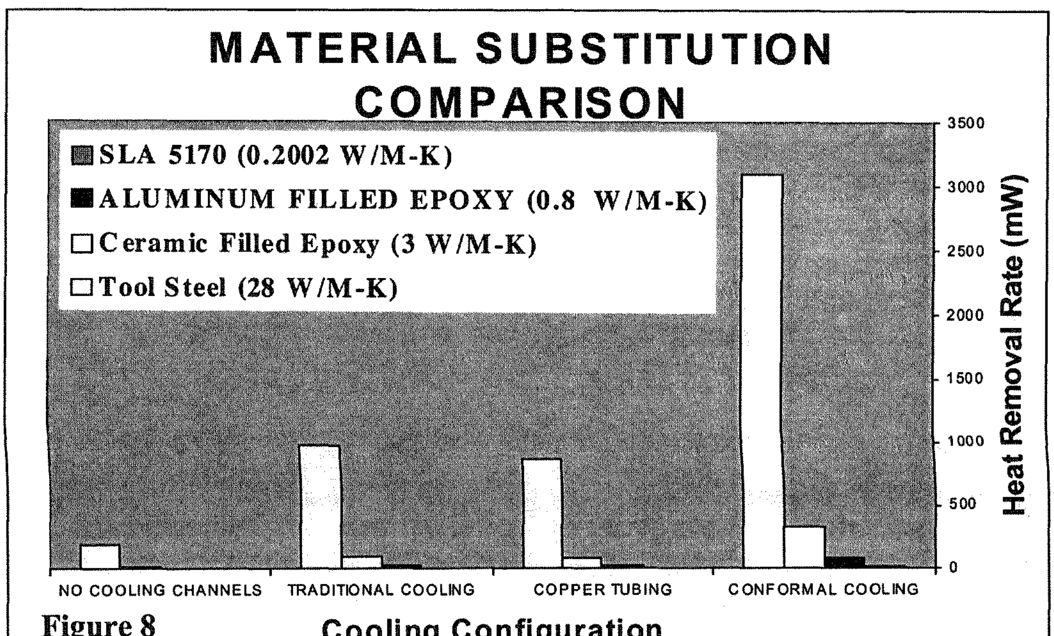

Figure 8

challenging to transfer heat through. Ceramic filled epoxy[7] is a significant improvement over aluminum filled epoxy while tool steel is even a greater improvement over the ceramic filled epoxy. Figure 9 illustrates the addition of aluminum and copper to figure 8, again a significant improvement over tool steel.

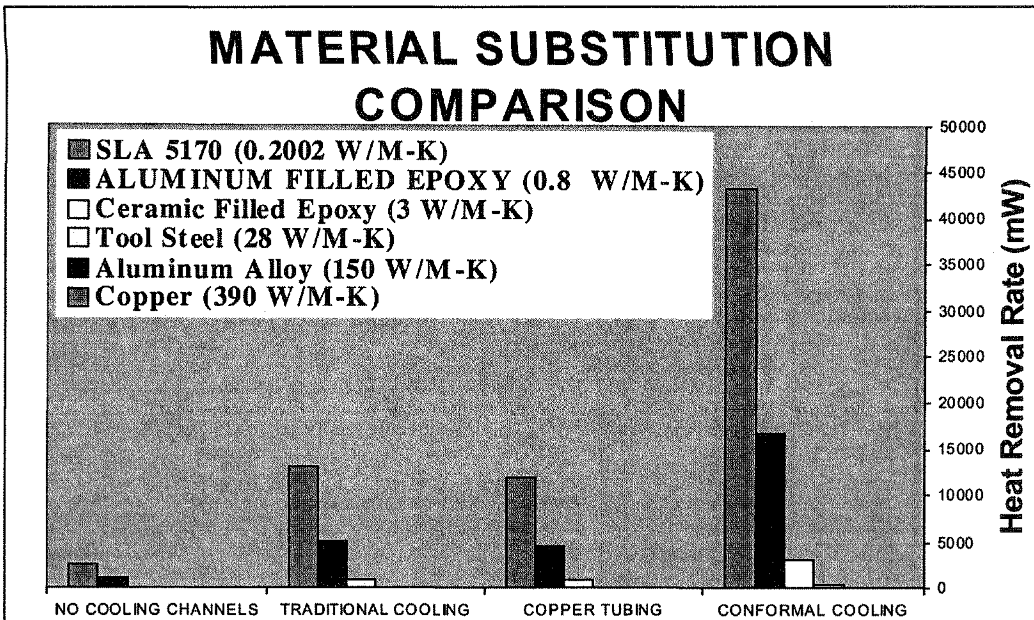

Figure 9

Conclusions

Any cooling is useful for standard tooling and rapid tooling. If channels of any form are created within a mold, heat removal rates can improve as much as three times with formed copper or traditional cooling and nine times with conformal cooling.

Conformal cooling is a significant improvement over traditional cooling and formed copper cooling and may increase mold life by reducing thermal shock after plastic injection.

Conformal cooling has significant potential for reducing cycle times by improving heat removal from injection molded parts.

To cool detailed features of parts cooling channels should be located as closely to the cooled surface as possible while still maintaining structural integrity.

Mold materials with higher thermal conductivity will improve heat removal rates significantly over epoxy based materials.

Acknowledgments

We gratefully acknowledge the support of the National Science Foundation (EEC-99619715, Undergraduate Research in Solid Freeform Materials and Technology).

Thank you to the Rapid Prototyping Consortium and the Rapid Prototyping Center staff at Milwaukee School of Engineering for their contribution to this applied research project.

Thanks also to Rich Phillips of the Mechanical Engineering Department at Milwaukee School of Engineering for facilitating this project.

References

1. http://www.dtm-corp.com/Technology/Materials/rapidstl.htm
2. http://www.prometal-rt.com/
3. Sachs, Emanual, Samuel Allen, Honglin Guo, James Banos, Michael Cima, James Serdy, and David Brancazio, "Progress on Tooling by 3D Printing; Conformal Cooling, Dimentional Control, Surface Finish, and Hardness," 1997 SFF Symposium Proceedings pp 115-123
4. Bartkus, Eric K., Chuck Ondrejka,"Rapid Product Development and Tooling at Amway Corporation," 1999 Rapid Prototyping and Manufacturing Conference Proceedings, pp 205-216
5. Gervasi, V., L. Milkowski, J. Canino, R. Zick, "MSOE TetraLattice, Applications and Simplified CAD Representation," SFF Symposium Proceedings, August 1999
6. http://www.3dsystems.com/index_nav.asp?nav=products&content=products/index.asp
7. Adtech EC-430, ceramic filled epoxy tooling system, product bulletin
8. Rao, Suanth,"How to make Injection Molds," Hanser Publishing, Munchen, Germany