# FEASIBILITY OF CERAMIC CASTINGS FOR CONFORMAL COOLING BLOW MOLDS

Benjamin H. Peterson
Chemical and Materials Department
Arizona State University
Tempe, Arizona 85287

Rapid Prototyping Center
Milwaukee School Of Engineering
1025 North Broadway
Milwaukee, Wisconsin 53202

Faculty Advisor: Vito Gervasi

## Abstract

A potential method to reduce cycle times and enable blow molds to run at higher temperatures is to integrate TetraLattice$^{TM}$ conformal cooling into production tooling. TetraLattice$^{TM}$ has been shown to improve heat removal rates by four times that of conventional cooling in injection molding configurations and will likely provide a notable improvement for blow mold tooling as well. Implementing TetraLattice$^{TM}$ conformal cooling in metal molds is still being investigated since conformal cooling channels of curved surfaces cannot be achieved using a purely subtractive method. The specific goal of this research was to create a method to manufacture chrome-copper blow molds with TetraLattice$^{TM}$ conformal cooling channels. This study specifically addresses the feasibility of using cast ceramic as an expendable core to create a coolant flow path in a mold casting process. The parameters of overall channel height, distance between supports, and leg diameter of the TetraLattice$^{TM}$ flow paths were the focus of this research. These parameters were used to determine the maximum allowable stresses cast ceramic can safely support before possibly failing during the metal casting process. The results of this study have shown that cast ceramic is strong enough for a metal casting process and further investigation will allow for the study of an actual casting process.

**Keywords: Blow-mold, Conformal Cooling, TetraLattice$^{TM}$, Ceramic Expendable Core**

## 1. Introduction

### 1.1. background

Each day millions of plastic bottles and containers are created by a process known as blow molding. Blow molding consists of heating plastic material until it reaches a viscous state, which is then blown with air to fill the void of a mold (Figure 1). Once formed to the mold, the plastic begins to cool and solidify to a hardened state, at which time the plastic part is ejected from the mold.

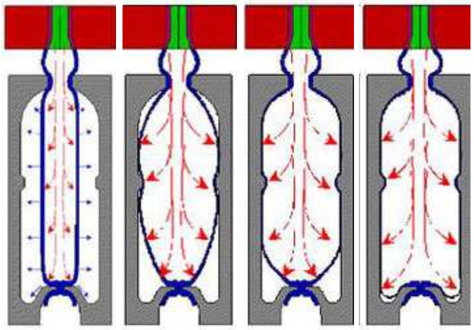


Figure 1: Different stages of the blow molding process in a progressive order

For one complete blow mold cycle, which is the amount of time between the start of two consecutively blown parts, the cooling time can account for about 84% of the total time (figure 2). The cooling time is the same as the blow time because the plastic begins to cool once forced against the mold wall. This cooling time is dependent on the size and material of the mold and also the thickness and material of the blown part. Decreasing the amount of time required to cool the part can significantly benefit the manufacturer by allowing for increased production rates and better product quality [1].

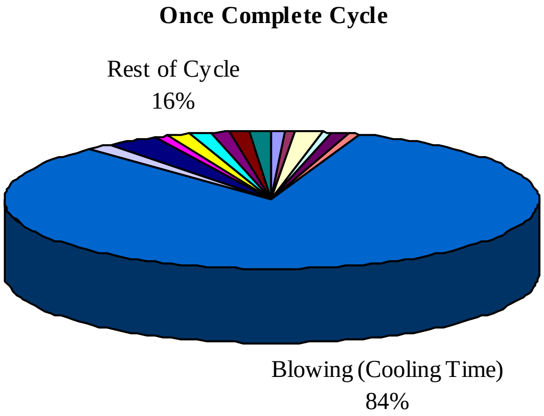
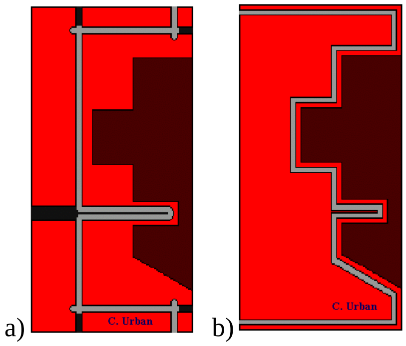


Figure 2: One complete blow molding cycle for a 250mL round plastic bottle [1]

Presently, cooling time is decreased by using a combination of thermally conductive mold materials and by manufacturing gun-drilled, line-of-sight cooling channels into the mold as seen in figure 3a. Coolant flows through the channels drawing heat away from the plastic part and the blow mold. Molds made of thermally conductive materials allow for increased conduction of heat away from the plastic part, allowing for faster solidification. Although these cooling channels can decrease the cycle time of the part, a better-designed system of cooling channels can be more efficient instead of straight, gun-drilled channels. A desired method for cooling is conformal cooling, which is achieved when cooling channels are placed equidistance to the mold surface completely around the part (figure 3b). Cooling channels placed closer to the plastic part and with greater surface area provide more equally distributed and faster cooling. As defined by E. Sachs, equation (1) represents the diameter, d, necessary to obtain conformal cooling for any given mold material, where k is the thermal conductivity, $\tau_{cycle}$ is the cycle time, and $\rho$ is the material density, and $C_p$ is the specific heat of the material [3].



Figures 3a and 3b: conventional (a) and conformal (b) cooling channels in molds [2]

$$d < \sqrt{\frac{k\tau_{cycle}}{\rho C_p}} \tag{1}$$

## 1.2. purpose

A configuration of channels known as TetraLattice$^{TM}$ has proven to be about four times as effective in removing heat as conventionally straight channels in injection molding configurations [2]. This lattice is an ideal cooling system because of its large cooling channel surface area to volume ratio and it can be close to the mold surface while maintaining the structural strength of the mold. TetraLattice$^{TM}$ channels mimic the configuration that exists in the diamond structure (figure 4), where each of the nodes of the TetraLattice$^{TM}$ represents a carbon atom. Since conventional subtractive methods such as CNC milling are not capable of creating the TetraLattice$^{TM}$ channels, this research investigates a specific method of integrating TetraLattice$^{TM}$ channels into metal. This method is a ceramic expendable core casting process. This process combines solid freeform fabrication additive techniques and traditional investment casting to produce a structure of TetraLattice$^{TM}$ conformal cooling channels in metallic blow molds (figure 5). Chrome-copper will be the blow mold material to be used during this investigation because of its superior strength compared to plain copper and its relatively high thermal conducting properties for better heat removal.

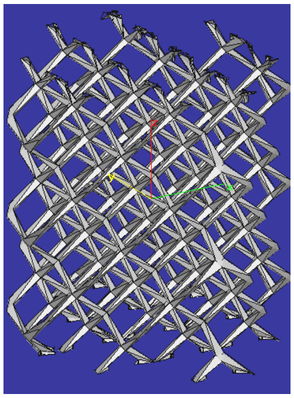


Figure 4: Simple TetraLattice$^{TM}$ structure

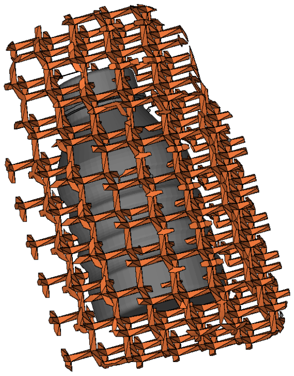


Figure 5: Example of TetraLattice$^{TM}$ conformal cooling around a bottle shape

## 1.3. scope

The scope of this work is to test the feasibility of the ceramic expendable core casting process. The bulk of this research is about ceramic since it is an ideal material that can endure the high temperatures of chrome-copper casting. Ceramic is a brittle material and its mechanical properties are weak compared to other materials and is a viscous material in its pre-hardened state. Hence, most of this research is to determine the strengths and properties of a particular ceramic and determining the benefits, problems, and solutions to potential problems.

## 2. Materials and Methods

### 2.1. stereolithogrophy apparatus (SLA)

Stereolithogrophy apparatus (SLA) is a solid freeform fabrication technique, or additive manufacturing process. The SLA is used to create a TetraLattice$^{TM}$ configuration layer by layer from a three-dimensional computer-generated design. The design is created by an automated ultraviolet laser rastered back and forth hardening only the top-most layer of photopolymer as in figure 6 [4]. This type of fabrication is very useful because it allows for complex geometries to be built that many other manufacturing techniques cannot accomplish.

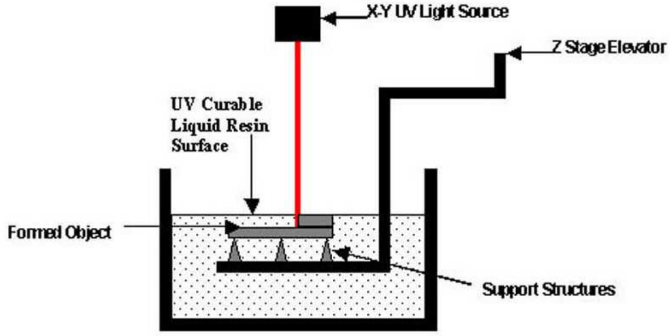


Figure 6: Diagram of the SLA process

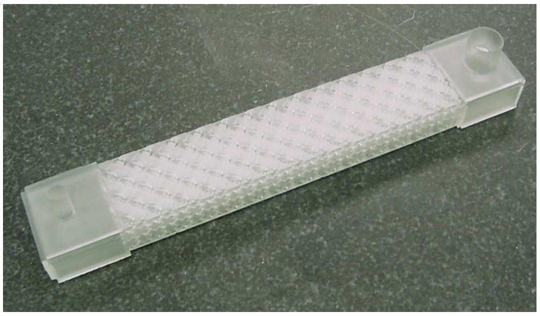


Figure 7: SLA TetraLattice$^{TM}$ pattern

### 2.2. ceramic expendable core process

The ceramic expendable core process involves five major steps. First, a hollow TetraLattice$^{TM}$ pattern is made on the SLA and is then filled with ceramic slurry (figure 7). The ceramic is a mixture of 180g of hardener to 1000g of phosphate bond silica powder. The hardener is 50% water and 50% mixture of silica in water. The ceramic slurry is degassed before it is used to fill the SLA pattern. Once filled with ceramic, the SLA pattern is left to cure for about 3.5 hours before put in the oven to thermally remove the SLA pattern and also fire the ceramic to make it stronger. The oven is set at 325 deg. F. for four hours then raised to 1800 deg. F. at a rate of 200 deg. F per hour. The temperature is maintained at 1800 deg. F. for an hour before being allowed to cool down to equilibrium with the oven door closed. The SLA burns off at about 500-600 deg. F but the ceramic fires at much higher temperatures [5]. Once the ceramic TetraLattice$^{TM}$ is revealed and cooled it is then placed in a ceramic mold to cast the desired chrome-copper blow mold. The ceramic mold will contain a ceramic shape of the bottle and any ceramic supports that will be needed to support the complex cooling channel structure during casting. Molten chrome-copper is cast into the ceramic mold and once the metal has cooled the ceramic is then leached out from the mold. Leaching is a process that chemically dissolves the ceramic, but also must be done without harming the newly cast metal. The mold is then ready to be used and compare its performance to conventionally cooled blow molds of the same size and material.

## 3. Theories, Models, and Hypothesis

The strength of a ceramic TetraLattice$^{TM}$ needs to be determined to know the probability of breaking during the chrome-copper casting process and during thermal removal of the SLA pattern from the ceramic. The difference in densities between the molten chrome-copper and ceramic during casting will induce forces in the ceramic due to buoyancy laws as depicted in figure 8. The complexity of the TetraLattice$^{TM}$ configuration makes mathematically finding the strength of the lattice very difficult if not impossible. Ceramic strength tests were performed by comparing the strength of a mathematically simple geometry of a rectangular beam of ceramic to a rectangular TetraLattice$^{TM}$ beam of ceramic with equal lengths, widths, and cross-sectional areas as depicted in figure 9. The strength of a rectangular beam for a distributed load is represented by the equation diagrammed in figure 9, where σ is the stress, F is the force, L is the length between supports, b is the width, and h is the height of the ceramic bar. The TetraLattice$^{TM}$ is a more complex geometry and the equation that defines its behavior is more complicated, but by experimentation a constant can be added to the equation to reference its strength values to those of the solid rectangular beam.

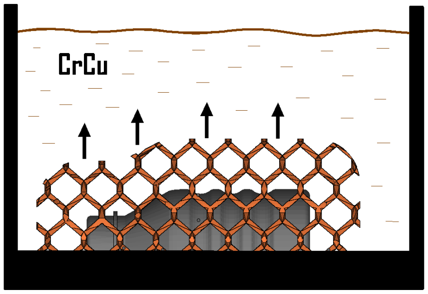


Figure 8: Diagram showing the forces due to differences in densities between the ceramic and CrCu metal.

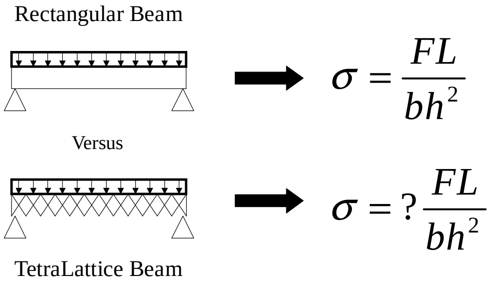
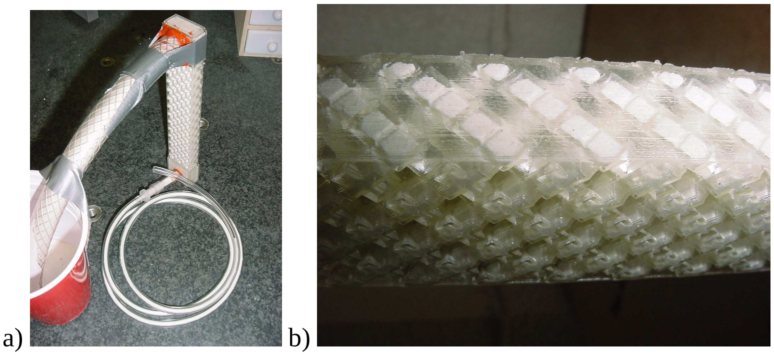


Figure 9: Correlation between the rectangular and TetraLattice$^{TM}$ beam.

## 4. Results

### 4.1. casting ceramic in SLA

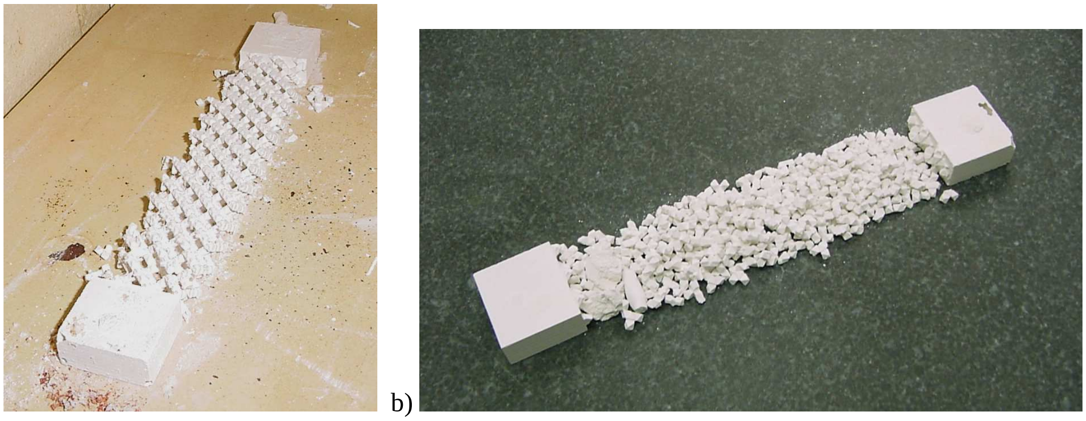
After the hollow TetraLattice$^{TM}$ SLA pattern is created, it is then filled with ceramic. It is imperative that this process be done correctly and accurately since getting high viscosity material to fill every corner of the TetraLattice$^{TM}$ pattern can prove to be difficult especially because of its short pot life (on the order of about seven minutes). A vacuum and pressure approach was employed to fill the SLA TetraLattice$^{TM}$ beam. As seen in figures 10a and 10b, the ceramic filled the TetraLattice$^{TM}$ structure to a fine detail. No voids of ceramic were noticed from a visual inspection, showing that the method of filling the ceramic was successful.



Figures 10a and 10b: Photos show that the ceramic filled the small detailed portions of the TetraLattice$^{TM}$ pattern.

### 4.2. thermal removal of the SLA pattern

Once the SLA pattern is filled with ceramic and has cured for 3.5 hours, it is then immediately placed in the oven to be thermally removed. The desired wall thickness around the TetraLattice$^{TM}$ portion of the SLA pattern was to be built with thin 0.017” walls to aid the thermal removal process. However, upon examination the wall thickness was actually between 0.03” and 0.04”, which was about twice as much as the desired thickness. The larger SLA wall thickness also made the volume of the ceramic less than anticipated. Since there is a difference in the coefficients of thermal expansion between the SLA pattern and the cured ceramic, the plastic SLA pattern will expand more than the ceramic inducing forces between the SLA and the ceramic. If the forces are too great the ceramic will break. The first trial of thermally removing the SLA broke the TetraLattice$^{TM}$ into many pieces as seen in figures 11a and 11b. It still may be possible to thermally remove the SLA if the wall thickness is made correctly and the ceramic has greater cross-sectional area.

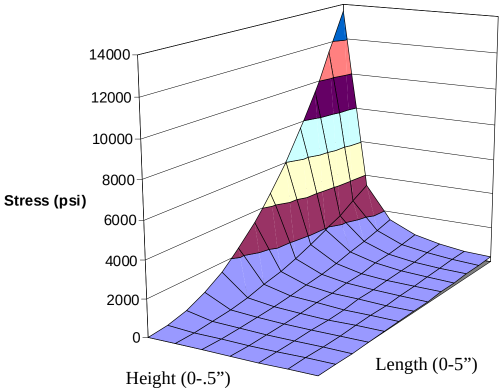

a) b)

Figures 11a and 11b: Photos show the ceramic after SLA thermal removal, which was in many pieces.

## 4.3. ceramic strength testing

For a general understanding of the strength of the ceramic, simple bending tests were performed. The tests were performed in accordance with the ASTM Standard 1161-02c except for a few changes [6]. The goal was to test an actual ceramic TetraLattice$^{TM}$ structure however in a three-point or four-point bend test there is not a specific place for the loads since the TetraLattice$^{TM}$ structure does not have a continuously flat surface. Also, buoyancy forces are equally distributed load forces, hence a distributed load test as shown in figure 9 above was performed to mimic the actual conditions the ceramic would be in during metal casting. The goal was to compare the TetraLattice$^{TM}$ to solid rectangular ceramic bars of equal length, width, and cross-sectional area. To achieve those criteria the dimensions of the rectangular beams were 5.0” by 0.5” by 0.5” and the TetraLattice$^{TM}$ beams were 5.0” by 1.1111” by 0.5” because the TetraLattice$^{TM}$ beams were approximately 46% ceramic and 54% void.

The following three-dimensional graph in figure 11 shows the amount of stress created in a beam of a specific height and length between supports from the rectangular beam stress equation in figure 9 above. The force is held constant at an equivalent of 12” of chrome-copper molten metal above the ceramic and the width of the beam cancels out of the equation when the volume of the molten metal is also substituted into the equation to calculate the induced forces. The results of the strength testing of the rectangular beam are summarized in table 1. The dimension of the ceramic can be considerably small before the stresses are too great, for the desired application of introducing cooling channels into blow molds.

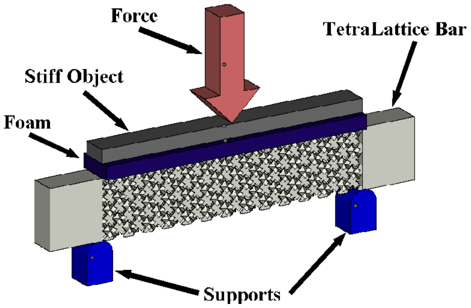


Figures 11: Graph of stress in a distributed load beam test as a function of height and span length with force and width held constant.

Table 1: solid rectangular beam ultimate strength results

| | |
|---|---|
| Average Stress (psi) | 5631 |
| Stnd. Dev. | 1117 |
| 99.7% Safe (psi) | 2281 |

Since the TetraLattice$^{TM}$ was not tested as a result of the failure to successfully thermally remove the SLA pattern, it will be tested later as shown in figure 12. Once it has been tested, correlation can be made between the ceramic rectangular beam and ceramic TetraLattice$^{TM}$ beam.



Figures 12: Configuration of the loading mechanism for testing.

## 5. Discussion

The results of the tests show that the ceramic will most likely be strong enough for the application of casting metal around the ceramic. With further investigation of the strength of ceramic TetraLattice$^{TM}$, it will be determined if the metal casting can be done and what dimensions the ceramic TetraLattice$^{TM}$ will need to be for effective casting (figure 11). The ceramic expendable core process involves many steps and can be time consuming, but the steps are relatively inexpensive and the results can potentially save more money than is needed to complete the process using other potential methods. It should also be noted that most of the molds currently being used were manufactured by a subtractive method from a pre-machined block of metal. Pre-machined blocks are advantageous compared to cast molds because they are typically harder and stronger. However, the cast chrome-copper should be strong enough for the blow mold process and a harder mold is not necessarily needed. This research can also be applied for use in different types of molds, such as injection molds. Injection molded parts involve greater pressures so the molds must be stronger than blow molds to withstand the higher pressures. The TetraLattice$^{TM}$ cooling channels are structurally stronger than conventional cooling channels, allowing the TetraLattice$^{TM}$ channels to be placed closer to the mold surface to be more efficient at removing heat from the plastic.

## 6. Conclusion

TetraLattice$^{TM}$ cooling channels are significantly more effective at removing heat from molds than conventional cooling channels, but because of their complex geometry current subtractive methods are unable to implement them into current blow mold applications. The ceramic expendable core process is a novel method to introducing such complex geometries into metallic molds. This process was investigated and the results have shown that it may be an excellent alternative to current manufacturing methods if it is further developed. Specifically the process of thermally removing the SLA from the ceramic needs to be further investigated.

## 7. Recommendations

It is recommended that the thermal removal of the SLA be further investigated, by either increasing the ratio of ceramic volume to SLA volume or by reducing the thickness of the SLA walls to reduce the force exerted on the ceramic when it expands. There are also different solid freeform fabrication techniques that may be applied to introduce cooling channels into metallic molds easier. One such process may be to create the ceramic TetraLattice$^{TM}$ channels directly from a solid freeform fabrication machine that produces ceramic parts, firing it, casting it in metal, and then leaching out the ceramic pattern. That technology was not available to the author.

## 8. Acknowledgements

The author would like to recognize the Milwaukee School of Engineering (MSOE) and the National Science Foundation (NSF) for funding and support of the 2003 Research Experience for Undergraduates (REU) program. Special thanks and recognition goes to Vito Gervasi (Advisor) for his advice and expertise and Ann Bloor for her support. Other thanks include the members of the Rapid Prototyping Center Research team for their added assistance in performing some of the experimentations.

## 9. References

[1] Ravell, G. “Information about typical blow mold process time and costs.” *Interview on cycle times of blow molding processes.* August 2003.
[2] Gervasi, V. “Conformal Cooling: Prospective Cycle-time Reduction and Future Applications.” *Moldmaking Expo: Engineer, Build Repair Proceedings*, 2002.
[3] Sachs, E., Wylonis, E., Allen, S., Cima, M., and Guo, H. “Production of Injection Molding Tooling With Conformal Cooling Channels Using the Three Dimensional Printing Process.” *Polymer Engineering and Science*, Vol. 40, May 2000.
[4] http://www.msoe.edu/rpc/sla.shtml. “Stereolithography Apparatus, SLA.” *Rapid Prototyping Machines at Milwaukee School of Engineering*.
[5] Rocholl, J. and Bollman, J. “Ceramic Procedures.” Interview about Ceramics. July 2003.
[6] Standard Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature. ASTM International. C1161-02c.

## Disclaimer

This material is based upon work supported by the National Science Foundation under Grant No. EEC-0139142. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.