Optimizing the Tetrashell Build Structure to Reduce Shell Cracking in the Autoclave with SLA Patterns

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Background

From the first introduction of additive manufacturing in the late 1980's, there was a great deal of interest in being able to create prototype patterns for investment casting. The ability to print prototype patterns would allow prototype castings to be created without the cost and lead time associated with creating wax pattern tooling.

Early trials with stereolithography (SL) patterns had very limited success. Thermal expansion of the solid pattern tended to crack and fracture shells in the autoclave, rendering the shell useless. PCC personnel stated that even with additional coats on the shell, success rates were in the 20% range. Five patterns would be processed in hopes of obtaining one prototype casting.

In 1992, 3D Systems developed the QuickCast build style, which hollowed the pattern and used an internal support structure to hold the walls of the pattern in place and keep them from flexing. Initial versions used square and triangular support structures, but eventually a hexagonal support structure was adopted. The hollow build style was thought to provide two advantages. First, it significantly reduced the resin mass that must be burned out of the shell, thus reducing both burn out times and residual ash. Second, and more importantly, because it was hollow, the pattern could collapse inwardly as it expanded with heat, reducing the pressure exerted on the shell and reducing the likelihood that the shell would crack in the autoclave. While the incidence of shell cracking was reduced significantly, shell cracking continued to be the major cause of failure of SL patterns in investment casting.

Another hollow build structure called Tetrashell, was developed at the Milwaukee School of Engineering as an alternative to the hexagonal internal structure. A change in the internal structure suggested it may have the potential of reducing the incidence of shell cracking. This investigation was initiated to evaluate the shell cracking tendency of the Tetrashell structure relative to the QuickCast structure.

The QuickCast Structure

The QuickCast build style appears to be a hexagonal cell structure when viewed from the top. However, only two sides of the hexagon are created at any one time. Opposite sides of the hexagon are built for several layers until a short wall is built. Then the build shifts and another pair of opposite sides are built until the height of the cell wall is reached. Finally the third set of walls are built completing the hexagon. The process is repeated until the pattern is completed. Figure 1 shows the internal structure. Note that the completed support structure is very open and allows fluid to drain throughout out the structure. An open structure is important. If closed cells were used, uncured resin would be trapped inside the pattern and would be solidified in the post cure process.

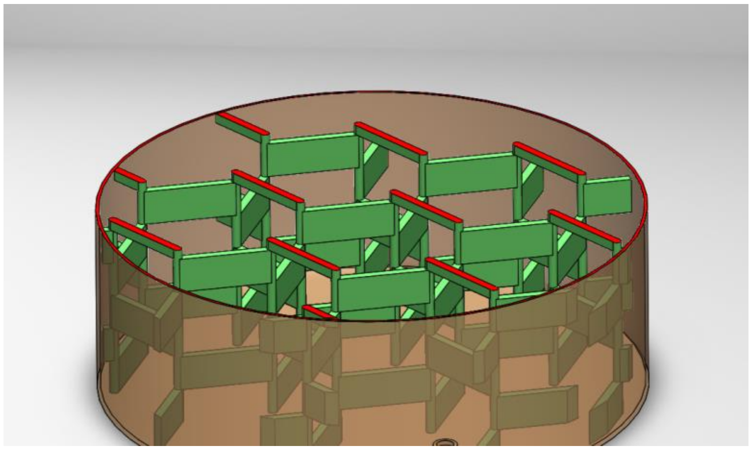


Figure 1. QuickCast internal structure.

One disadvantage of this structure, however, is that the structure creates a post at every corner of the hex that runs from skin to skin. That post, illustrated in Figure 2, is supported over its entire length by the short walls that create the hexes. With the reinforcement provided by those short wall sections, it is virtually impossible for the post to buckle. The pattern is built hollow so that it can collapse inwardly as it expands with heat. However, the reinforced posts at each corner of the hex effectively prevent the pattern from collapsing. Consequently, the

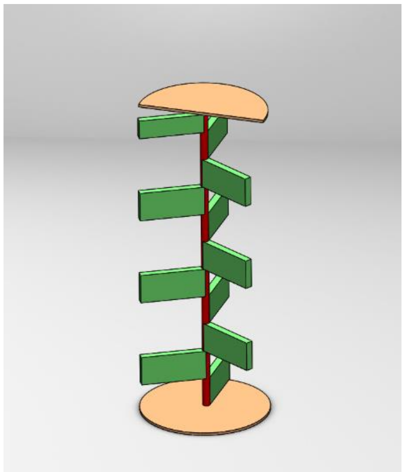


Figure 2. Post at the corner of the hexagonal support structure.

pattern expands nearly as much as if it were a solid pattern and in spite of being hollow, thermal expansion of the pattern is likely to crack the shell.

A work around was developed to minimize the chances of shell cracking. If the pattern was vented, and the skin of the pattern was punctured, steam could enter the interior of the pattern as soon as the autoclave was pressurized. The steam quickly heats the internal structure and it softens to the stiffness of a gummi bear. With that softness, now the rod can buckle and the pattern can collapse inwardly as intended.

This process is used by nearly all foundries who use QuickCast patterns to minimize the chances of failure in the casting process. While it works very well, it adds quite a bit of effort, cost and time to the casting process:

1. To make it through the autoclave, at least one vent must be added to each pattern. Patterns larger than 6 inches or so will require multiple vents. Vents can be created with a piece of spaghetti wax, or a more complex molded vent can be used. The vent must be attached to pattern during assembly. In most cases, a hole through the skin is drilled prior to placing the vent and the vent covers the hole. The pattern is then shelled normally.
2. After the shell is complete, the vent must be opened so that there is a pathway to the interior of the pattern for steam to enter.
3. After the autoclave process, the pattern is burned out. After burnout, the shell is cooled to clean out any ash and to patch the vents. Vents must be patched to prevent molten metal from leaking out during pouring.
4. After the casting has cooled, the vent stubs must be ground flat.

All these additional steps add cost and time to the casting process. Most importantly, they add labor to the casting process.

The Tetrashell Structure

Like QuickCast patterns, Tetrashell patterns are also hollow with an internal support structure. However, the internal structure is very different. The basic unit of the support structure is a "V" made of two legs. A second "V" is inverted, rotated 90 degrees, and joined to the first as shown in Figure 3. This 2-V basic structure is repeated to create the internal structure. Figure 4 shows several basic units connected to form the internal support structure. Like QuickCast, It is a very open structure and will allow drainage from all points of the pattern. However, unlike QuickCast, there are no posts running from skin to skin. This should allow the pattern to collapse internally much more easily than QuickCast patterns.

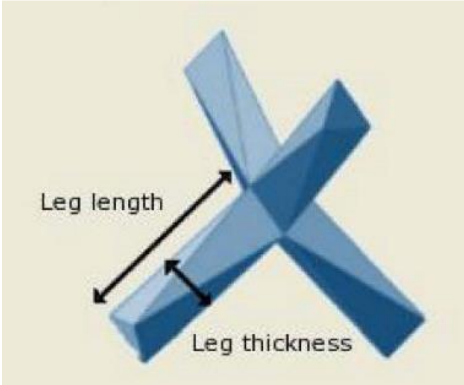


Figure 3. Basic unit of tetrashell structure

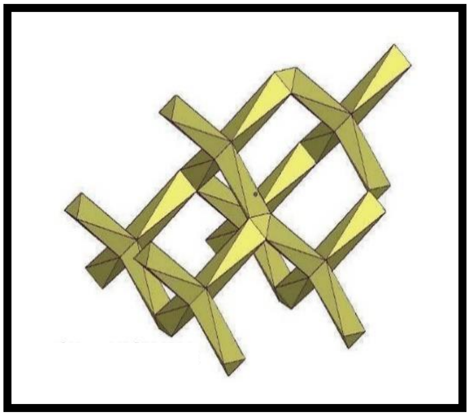


Figure 4. Internal structure of a Tetrashell build style.

Force Exerted on the Shell from Thermal Expansion

The pressure exerted on the shell by the pattern as a result of thermal expansion is given by

$$P = k * CTE*(T_2-T_1)*h$$

Where P= *pressure exerted*

k = *stiffness of the structure per square inch*

CTE = *coefficient of thermal expansion*

T_2 = *Temperature of the autoclave*

T_1 = *ambient temperature*

h = *the thickness of the pattern*

To illustrate, consider Figure 5. In view a, a part is at ambient temperature T_1. In view b, the temperature has been raised to T_2 and the part has expanded. That expansion is equal to the CTE times the increase in temperature. In view c, an external force has been exerted on the top of the part to compress it back to its height at T_1. This is the force that would be exerted on the shell over the same temperature rise.

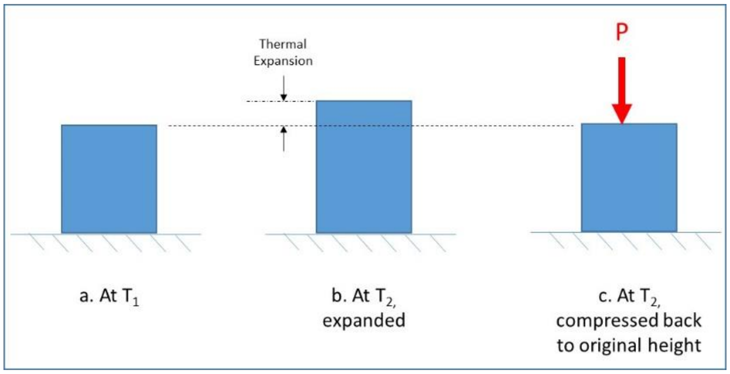


Figure 5. Illustration of the formula for pressure exerted on the shell.

The CTE is published for most SLA resins and the ambient and autoclave temperatures are similar for nearly all foundries. What is not known is the stiffness of QuickCast and Tetrashell structures. Once the stiffness, is known, the pressure exerted on the shell can be calculated. The next step is to determine the stiffness.

Test Plan

To determine the stiffness of the internal structures, test specimens were created as shown in Figure 6. All specimens were a flat disk 0.28” thick and 2.2” in diameter. The smaller height section around the circumference was ground off after the part was built. It was removed to provide a break in the outer wall so that the stiffness of the outer wall would not influence the measured stiffness of the pattern.

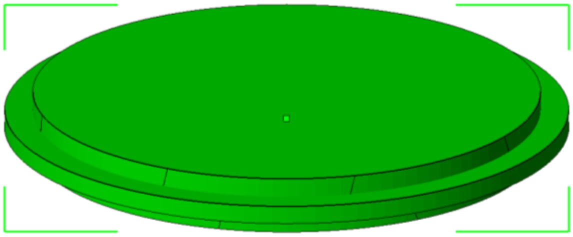


Figure 6. Test specimen

Both QuickCast and Tetrashell provide some user control over the density of the support structure. In QuickCast, you can control the size of the hatch and the height of the short walls that make up the sides of the hex. In Tetrashell, you can control the thickness of the leg and the length of the leg. The values selected for these build parameters significantly influence the stiffness of the structure created.

For the test, both QuickCast and Tetrashell specimens were created using a range of build parameters. All specimens were built using the DSM Element resin to ensure that differences in resin properties did not influence the measured stiffness.

Nine QuickCast specimens were built, three each with 0.100”, 0.175” and 0.25” hatch spacings.

Thirteen Tetrashell specimens were built with six different combinations of build parameters. They included the following:

Leg Length (in)	Leg Diameter (in)	No. of Specimens
0.162	0.025	3
0.162	0.030	4
0.217	0.025	3
0.217	0.030	1
.0325	0.025	1
.0325	0.030	1

The center outer ring was trimmed off on each specimen to eliminate the influence of the circumferential wall.

The stiffness of each sample was then measured in a tensile/compression test machine. Figure 7 shows one of the Tetrashell specimens mounted in the test machine.

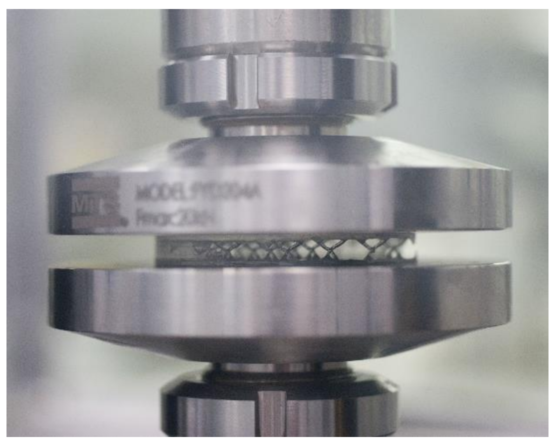


Figure 7. Specimen mounted in compression tester.

The test machine gradually increased the compressive force until a specified displacement was reached. The maximum force and displacement were recorded. Dividing the force by the displacement provided the stiffness of the sample. Dividing that stiffness by the area of the specimen yielded the stiffness per square inch of pattern. The stiffness obtained for multiple specimens were averaged to obtain the result.

Of course, that number will vary with the thickness of the specimen. All specimens were built to the same thickness so comparisons between specimens can be made.

Since all specimens were made from the same material, the amount of thermal expansion would be the same. The temperature in the autoclave rises approximately 175F (75F to 250F). The CTE of the Element resin is 76.1E-6 in/in/F and the thickness of the specimen was 0.28 inches. Consequently, the thermal expansion is 0.003729 inches.

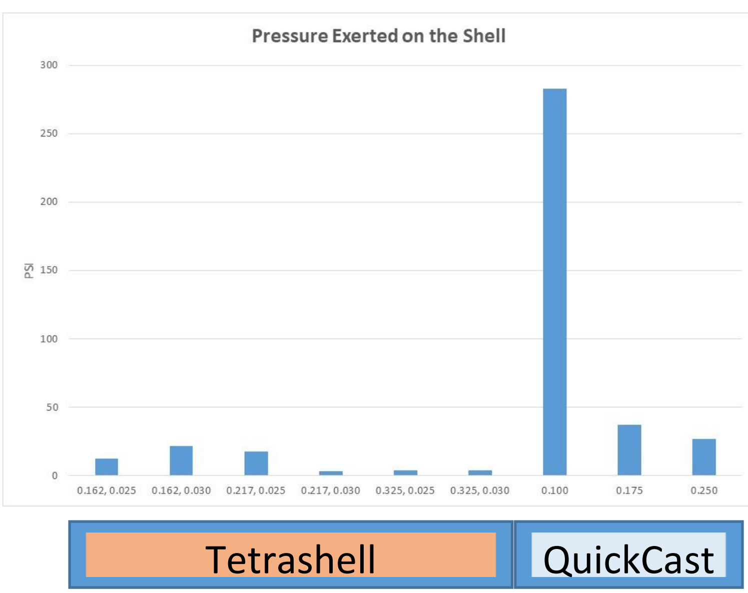
The measured stiffness is then multiplied by the thermal expansion to obtain the pressure exerted on the shell.

Results

The results are detailed in the following table.

Type	Parameters	k, (lb/in/in^2)	CTE	T_2-T_1, °F	Expansion	Press. (lb/in^2)
Tetra Shell	0.162, 0.025	3,399.4	76.1	175	0.0037289	12.68
Tetra Shell	0.162, 0.030	5,821.2	76.1	175	0.0037289	21.71
Tetra Shell	0.217, 0.025	4,756.2	76.1	175	0.0037289	17.74
Tetra Shell	0.217, 0.030	895.2	76.1	175	0.0037289	3.34
Tetra Shell	0.325, 0.025	991.1	76.1	175	0.0037289	3.70
Tetra Shell	0.325, 0.030	1,130.6	76.1	175	0.0037289	4.22
QuickCast	0.100	75,819.0	76.1	175	0.0037289	282.72
QuickCast	0.175	9,912.9	76.1	175	0.0037289	36.96
QuickCast	0.250	7,205.6	76.1	175	0.0037289	26.87

The results are also shown graphically in the column chart below.



Summary of Results

1. Pressure exerted on the shell by QuckCast patterns ranged from 26 to 282 psi. The tighter the hatch spacing, the greater was the pressure exerted.
2. Pressure exerted on the shell by Tetrashell patterns ranged from 4 to 22 psi. The higher pressures were observed with shorter leg lengths.
3. A QuickCast pattern with hatch spacing of 0.100 will exert 84 times as much pressure as a Tetrashell pattern with 0.217 in leg length and a 0.025 inch leg diameter.

Conclusions

1. Moving to a Tetrashell buld style from a QuickCast build style will significantly reduce the likelihood of shell cracking in the autoclave.
2. Patterns built using the Tetrashell build style will likely not require the multiple vents typically required on QuickCast patterns to prevent cracking in the autoclave, eliminating assembly labor, vent patch labor, and vent stub grinding labor.

Follow-On Work

In the next few months, these results will be confirmed in actual autoclave tests.

Acknowledgements

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