I. The Premise

A lot has changed in the last 20+ years. Just two short decades ago our top speed personal computer processors were clocked at 386 MHz, hard drive space and RAM memory were still measured in megabytes and you were lucky to have a 120 Meg hard drive!

Figure 1

Remember when your cell phone just made phone calls?

In the late 1980s cell phones came in a bag or a brick. Today's cell phones have more capacity, speed and functionality than what used to take up the entire desk space. It can even tell me where I parked my car!

But what does this have to do with prototyping you ask?

Everything.

As you've no doubt seen the demand for high tech gadgets has grown exponentially over the recent years. With it also came the demand for today's electronics to do more in less space. Just 10 years ago, a large capacity 3 Gig hard drive was the size of a small loaf of bread. Today it would be more likely compared to a stick of gum (and you can buy it right next to the gum at the grocery store).

Figure 2

Along with this demand came pressures and expectations on manufacturing to follow suit. New advances in technology reached all levels of product design. The PC became the primary tool for development. Automation and assembly became more sophisticated and new ideas stretched the known into the un-known.

Fortunately cell phones and computers were not the only things that have advanced in recent times, so have all of the surrounding support, design and manufacturing processes as well.

Figure 3

From this demand, processes like micro-molding were born. Known injection molding standards and techniques were being challenged to produce smaller, more complicated and tighter toleranced parts and components. And as the demand for micro-molded plastic parts grew so did the expectations on the technology.

A major part of that demand was the expectation that standard development processes would easily translate down to the micro (just smaller). It's expected that the same procedures for "large" product development like standard processing materials, equipment, packaging, pricing, and yes prototyping can be followed.

It is reasonable to expect that before any part goes to production that it first be prototyped. Webster's defines prototyping as, "an original model on which something is patterned, a first full-scale and usually functional form of a new type or design of a construction.[1]" There is an inherent expectation that prototyping provide some valuable information in the design process.

What is difficult is the fact that not all prototyping methods can produce every expected outcome when dealing with such small parts and features. The expectations that micro prototypes deliver the same valuable data to the process is no less important that their large counterparts. Therefore, there is a gap in the traditional process that needs filling.

The goal of this presentation is to discuss the various methods, challenges and variables for prototyping micro-sized and/or micro-featured plastic parts. It is also important to recognize that every part design is different requiring different features, tolerances, materials, etc. Through this discussion you might gain some new understanding as to the different tools and resources available today that might help you as you develop your next generation of products.

II. The Set-Up

In the world of micro molding you're usually talking about fairly small parts, some with extremely tight tolerances or features. So we decided to put it to the test.

This study created a test part of average size and detail to put through the process of building prototypes. The part contains many of the same features commonly found in micro molded parts today. The part contains thin wall sections, surface profiles, small features and fine details that represent many of the same part dimensions that medical, optic, and micro electronic industries require.

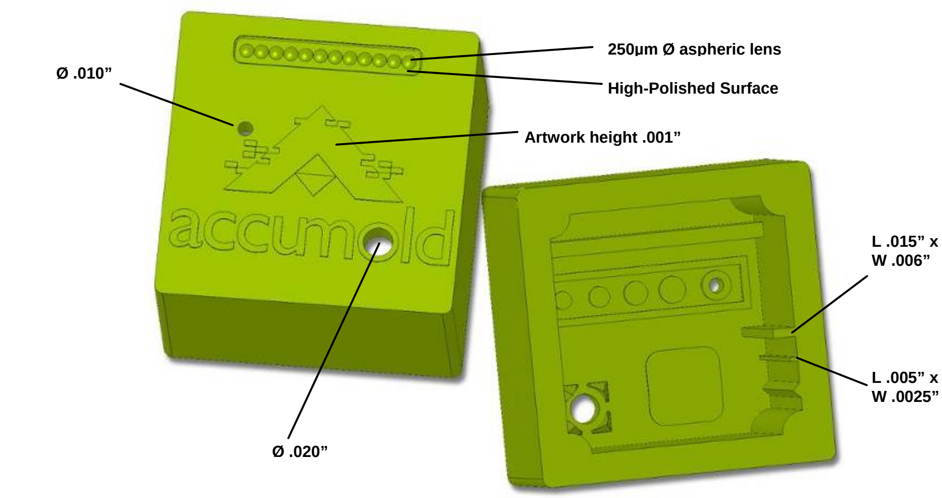

Figure 4

This part's basic dimensions are .200" x .200" x .125" (5.08mm x 5.08mm x 3.175mm). The other main features are; .010" (.254mm) and .020" (.508mm) diameter through holes, .015" x .006" (.381mm x .1524mm) and .005" x .0025" (.127mm x .0635mm) thin wall sections, and a highly polished surface with twelve 250µm (.009846") diameter lenses. This part also contains several other delicate features and embossed details.

This by no means says every part is this complicated nor does it exhaust the list in extreme features. Our challenge was to make a reasonably complicated part and put as many of the modern prototyping methods to the test. We wanted to see what features would translate and which would not.

The idea was not to claim one process over another but merely show the results of as many of these process that we could. Since not all situations are the same, some of these process could work quite well while others may not.

III. Comparison Criteria

For this experiment our main goal was to test the physical limitations of as many modern prototyping processes as we could. However, we know that there are many other considerations when choosing a prototyping method. Materials, color, strength, lead time, tooling/mold requirements, cost, mass manufacturability, change orders are just a few of the other criteria we looked at when working through the research.

IV. The Options

At the onset of just about any project one must decide many things, not the least of which is what prototyping method is best for their situation. Most part designers are not lucky enough to skip this stage and go right to production. Therefore, some solid decision making is at hand.

For the purpose of this discussion we'll be looking at the various prototyping methods through the "micro" lens. The goal is to approach each method assuming you are looking for an extremely small part, a complex geometry, very tight tolerances, or quite possibly all three.

This presentation will take a "micro" look to compare some of the more popular fabrication capabilities: Stereolithography (SLA), 3D Printing, PolyJet, Fusion Deposition Modeling (FDM), Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM), Cast Urethanes, Machining/Rapid Tooling, Rapid Injection Molding (RIM), and Standard Hard Tooling.

a. SLA - Stereolithography

Stereolithography is the process by which liquid UV curable photopolymer resin is subjected to a UV laser beam that layer by layer builds three dimensional parts. A layer at a time the UV laser traces a cross-section of the desired part. The UV laser hardens the liquid resin and bonds it to the layer below. Little by little the 3D part emerges from the liquid as the part layers rise.[2]

"Once the model is complete, the platform rises out of the vat and the excess resin is drained. The model is then removed from the platform, washed of excess resin, and then placed in a UV oven for a final curing. The model is then finished by smoothing the "stair-steps."[3]

Stereolithography was invented in 1986 by Charles W. Hull. Mr. Hull, considered the father of commercialized rapid-prototyping, coined the term to describe the process he discovered. His company, 3DSystems, started that same year and was very inflectional in developing many of the standards we still use today such as the .STL file format for model preparation.[4]

Stated Capabilities:

- +/-0.005" (0.127mm) for the initial inch, plus an additional 0.0015" for each additional inch. [5]
- High resolution build uses .002" layer thickness.
- In standard resolution, the minimum feature in the X-Y plane is 0.010" and the minimum in the Z axis is 0.016". In high resolution, the 0.003" laser beam spot enables smaller features. [6]
- photosensitive epoxy polymers [7]
- Stereolithography resins are now made to mimic a wide array of production plastics such as ABS, Polypropylene, and Polycarbonate. There are even some Stereolithography materials that are quite soft and flexible ranging from 45 shore A to 80 shore A in softness. [8]

Pros:

- Can produce parts very quickly
- No tooling required
- Inexpensive for low volume needs

Cons:

- Limited materials and colors
- Generally considered brittle
- Low resolution and tolerances when compared to micro molding
- Might not produce all fine features
- Parts don't represent actual molded parts
- Parts often limited to dimensional representation and not actual functional intent

Conclusion:

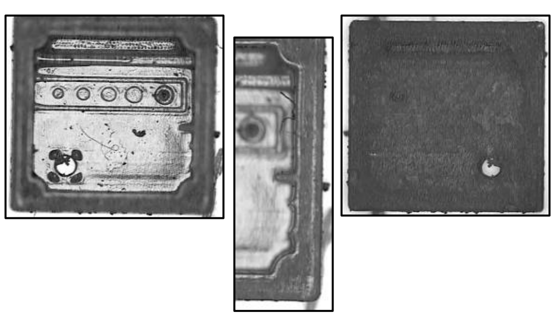

Figure 5 - 30X Zoom

Stereolithography is a great way to get prototype parts quickly with decent complexities. It works well for form and fit, especially if using over-sized models when compared to micro-sized parts. However, if the resin is a critical part of your prototyping analysis this process won't perform like a molded part. Many micro-sized parts or features may also be out of reach for such a process as well.

As you can see in Figure 5 our results produced the basic part shape and showed the process attempted most of the features. While the material is not transparent, the lens shape and the polished surface finish did not make it on the produced parts. Depending on what features are needed this process may not work. It's limited to specific photo-sensitive resins and can inherently inhibit testing of the finer details.

b. 3D Printing (Inkjet Printing)

Because stereolithography, as with many of the other additive fabrication processes, is often called printing it can sometimes be confused with this 3D printing method.

Just as the name implies, this method is very similar to what we commonly know as the standard ink jet printers many of us have on our desks today. However, instead of dropping tiny spots of ink on paper this process instead deploys tiny droplets of thermoplastic and wax. And in similar fashion to a SLA, layer by layer it forms cross-sections into complete and complex parts.[9]

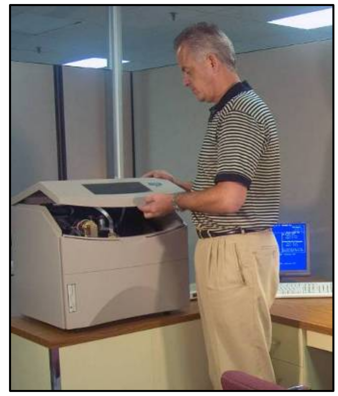

Figure 6

"When printed, liquid drops of these materials instantly cool and solidify to form a layer of the part. For this reason, the process if often referred to as thermal phase change inkjet printing. Inkjet printing offers the advantages of excellent accuracy and surface finishes. However, the limitations include slow build speeds, few material options, and fragile parts."[10]

Stated Capabilities:
- 0.0010 in. accuracy [11]
- Min feature size 0.005 in. [12]
- Min Layer thickness 0.0005 in. [13]
- Surface finish: Very Smooth [14]

Pros:
- Can produce reasonably fast when compared to hard tooling
- No tooling required
- Inexpensive for low volume needs

Cons:
- Very Limited material (2)
- Might not produce all fine features
- Parts don't represent actual molded parts
- Parts often limited to dimensional representation and not actual functional intent
- Generally considered brittle

Conclusion:
In our estimation this process doesn't seem to have caught on as much as some of the other additive methods available. Despite decent accuracy and smooth surface finish the limited material option may make this option not viable for many situations.

We could not find a vendor that felt confident their process would be successful with our part. We received no quotes due to the part and features sizes.

c. 3D Printing (3DP™ / Zcorp)

The other common use of the 3D printing term is a similar process to its inkjet friend. This MIT developed process known as 3DP™ distributes a powder and binder to form the three dimensional shapes. Zcorp is the only licensed user of this technology for the prototyping market. [15]

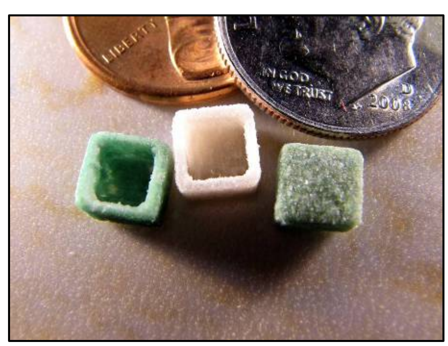

Figure 7

Stated Capabilities:
- 0.0035" Layer thickness[16]

Pros:
- Can produce parts very quickly
- No tooling required
- Can print in color
- Inexpensive for low volume needs

Cons:
- Surface finish not as smooth as other methods
- Micro features will be lost
- Brittle parts

Conclusion:

While this may be a quick prototyping method it's not considered to be very accurate in micro terms. There are only two material choices and the end parts are very brittle. For micro parts and features this is more than likely not a viable option. [17]

Figure 7 shows that this process gave us the basic shape however most of the other features were not present.

Again, depending on what features are needed this process many or may not work. Other rapid prototyping methods seem to produce more accurate parts for these size components.

d. PolyJet

The PolyJet process is very similar to SLA. The process deploys UV photo-sensitive liquid resin that is UV laser traced cross sections. The differences however are major. This method produces much thinner layers and cures the part in-line with the layering process.[18]

"PolyJet technology uses a jetting head to accurately build each layer at 16 microns (0.0006 inches) thick, which is about 1/5 that of stereolithography layers. The jetting head slides back and forth along the X-axis, jetting tiny droplets of UV resin onto the build tray. Immediately after building each layer UV bulbs alongside the jetting head cure and harden each layer subsequently."[19]

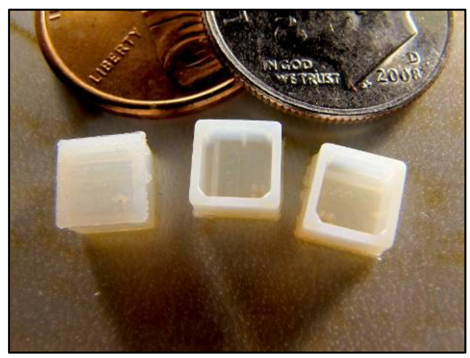

Figure 8

Stated Capabilities:
- Variety of photosensitive resins [20]
- 0.1-0.3mm (0.004-0.01 inch) typical (accuracy varies according to geometry, part orientation and print size). [21]
- Horizontal build layers down to 16-micron [22]

Pros:
- Can produce parts very quickly
- Higher resolutions than other additive processes
- No tooling required
- Inexpensive for low volume needs

Cons:
- Won't catch extreme micro features
- Doesn't represent actual molded part
- Parts often limited to dimensional representation and not actual functional intent

Conclusion:

Because the resolution is considered higher than other traditional process this could be a viable solution for micro-sized parts. It's quick and creates stable, strong, usable parts. The fine layering process produces very smooth surfaces and sharper details on finer features. [23]

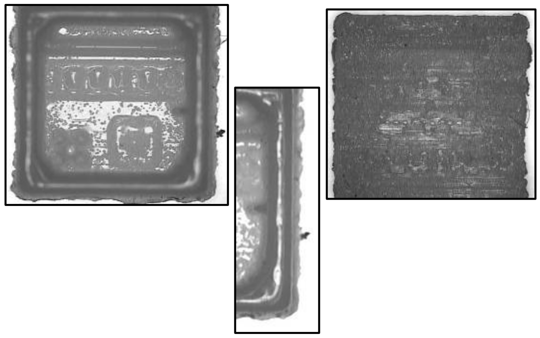

Figure 9 – 30X Zoom

Figure 8 (above) and 9 shows our results. Many of the fine features were lost and only in some of our samples did the larger through hole appear. The process also did not produce clean lines or edges.

We were told this process would be superior to SLA and according to the manufacturer's stated capabilities it should be. We were surprised by the results and for at least this part it wasn't much different than the SLA.

e. FDM – Fusion Deposition Modeling

FDM is again similar to the other additive modeling techniques. In this case the coiled modeling material is extruded through an extrusion nozzle that deposits small beads in layers that harden instantly. The nozzle can be programmed to deposit material both horizontally and vertically along the cross-sections of the part to form the desired shapes. This process offers several material options including a few production-grade thermoplastics such as ABS, Ultem and Polycarbonate. [24]

The Fusion Deposition Modeling (FDM) process first made its commercial appearance in 1990 and is currently a trademark property of Stratasys, Inc.

Figure 10

Stated Capabilities:

- ± 0.003 inch accuracy [25]
- 0.007 inch for higher surface finish and feature detail [26]

Pros:

- Production grade material selection, ABS, Ultem, or PC
- Decent accuracy
- No tooling required
- Can produce parts very quickly
- Inexpensive for low volume needs

Cons:

- Won't catch micro features

Conclusion:

Material performance always seems to rank high when it comes to the prototyping process which could be and advantage of the FDM process if your material selection is within its output selections. [27]

No vendor we asked attempted to produce this part with this process. One shop originally quoted our part then after further review no quoted it due to size and features and ultimately recommended a different process (PolyJet).

f. SLS – Selective Laser Sintering

"An additive layer-by-layer process, Selective Laser Sintering technology uses a high-temperature laser to melt and fuse, or sinter, powdered plastics or metal into a three-dimensional part." [28]

As the high powered laser beam passes over the fine powered material it fuses the tiny particles into solid cross-sections. The part is lowered and re-covered in powder as each layer is formed and the process is repeated until the part is complete. When compared to other methods, SLS has a wide range of powdered polymer material choices including some filled thermoplastics. [29]

Stated Capabilities:
- 0.004" in layers [30]

Pros:
- Closer to production like materials than SLA
- Stronger finished parts than SLA
- No tooling required
- Can produce parts very quickly
- Inexpensive for low volume needs

Cons:
- Not considered very accurate when speaking in micro terms

Conclusion:

SLS takes its advantage over SLA because of it has a broader material base however it's not necessarily more accurate than SLA and finer features may not be achievable. Not really considered a strong contender when accuracy or finer features are required. [31]

Figure 11

This was no quoted.

g. LOM - Laminated Object Manufacturing

Laminated Object Manufacturing is a process by which thin sections of plastic coated paper-like material is laser cut and layered to form three-dimensional objects. Hot rollers pass after each cut to bond, or laminate, each cross-section layer together. A post lamination process is required to remove excess material and can be time consuming. It's generally not considered to be as good as the other methods when it comes to surface finish, accuracy and stability of the finished part. [32]

Pros:
- Inexpensive material
- No tooling required

Cons:
- Not considered very accurate
- Won't catch micro features

Conclusion:

Not really an option when it comes to micro sized parts or features.

h. Cast Urethanes/ Rapid Tooling

Cast urethane molds, sometimes called rapid tooling, are produced by forming an impression of a sold part, usually produced by one of the other rapid prototyping methods, with an RTV (Room Temperature Vulcanizing) rubber mold. The mold is split and can reproduce 10-20 parts before the rubber mold begins to breakdown. [33]

"These parts have material properties similar to production-like plastics. It is possible to make these parts appear just like hard tooled

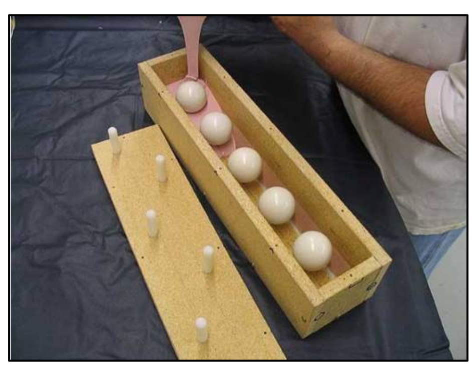

Figure 12

plastic parts through surface finish, color, accuracy, and material properties." [34]

Stated Capabilities:
- +/- 0.005" for the first inch, +/- 0.002" on every inch thereafter [35]
- Layer Resolution: 0.002" - 0.004"[36]

Pros:
- Much higher resolutions than additive processes
- Surface finish high quality
- Parts very close to injection molded parts

Cons:
- Requires a pre-built part (ie SLA, FDM) to make mold impression
- Part changes require a new cast.
- Mold will only produce a handful of parts

Conclusion:

The cast urethane process is only as good as the prototype part made via some other process by which to cast the impression in the urethane. Obviously from a micro view point this might not be of any help even if it can reproduce high resolution parts. You've got to have a part to make a part.

Since this requires a first part we didn't attempt this process.

i. Micro Machining

Micro machining is a subtractive method of shaping stock materials, like resin, through traditional milling and machining processes. The machining process can come in many forms, CNC, micro machining, laser machining, screw machining, etc. These methods turn, grind, drill, cut stock material to the desired shapes often through computer guided precision. [37]

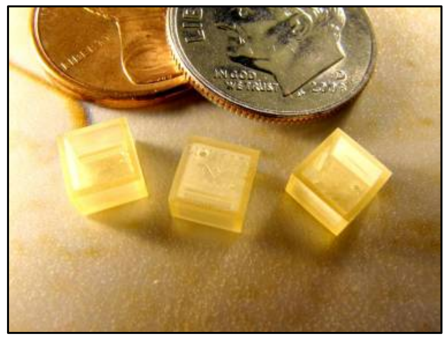

Figure 13 – Ultem Material

Stated Capabilities:
- 0.00008" (2 microns) [38]
- Repeatability 0.000008" (0.2 microns) [39]

Pros:
- Very high resolution
- No tooling required
- Wide production material selection

Cons:
- Slower process in quantity
- Expensive piece parts
- Part details limited cutting tool profiles.

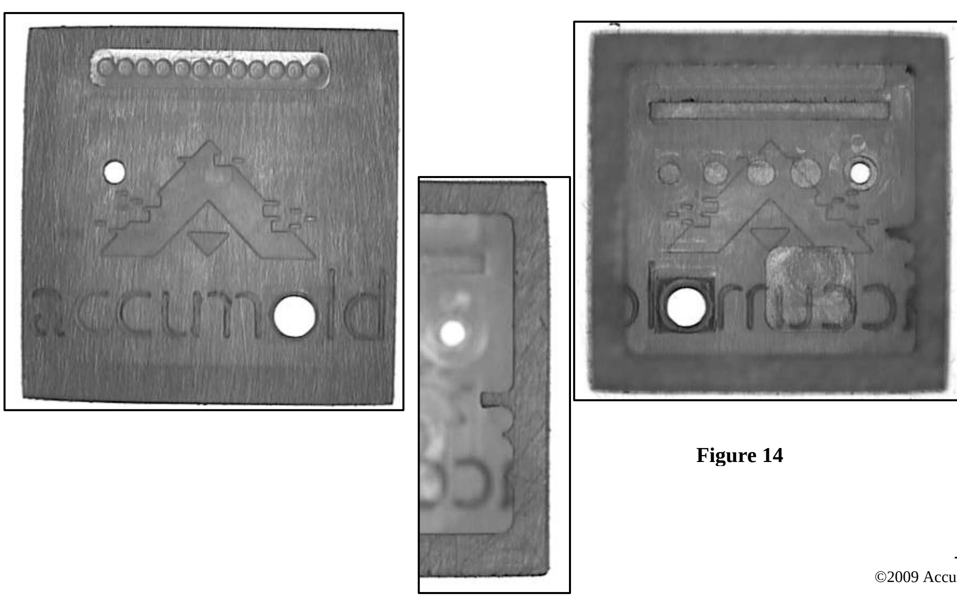

Figure 14

Conclusion:

From the micro viewpoint machined plastic parts can be very achievable. Machined parts do have high resolution and accuracy capabilities and can produce parts out of a very large array of production materials. Generally speaking this can be a great prototyping process for micro parts or features.

Our sample parts faired quite well using a micro CNC type process as you can see in Figure 13 and 14 above. Some of the features were rounded and the parts were not totally square but it could prove to be an excellent process for rapid prototyping.

We also attempted to produce a laser machined part but were told these were not producible with that method directly.

j. RIM – Rapid Injection Molding

Rapid injection molding is the process by which true injection mold tooling is produced to replicate parts. Unlike some standard production tooling this process often employs soft aluminum tools and a tight set of design criteria. Molds can be produced fairly quickly and be a good source for low-volume production.[40]

Figure 15

Stated Capabilities:

- Relativity tight tolerances
- Very good repeatability

Pros:

- Inexpensive tooling
- Fast turn times for tooling
- Can produce a good volume of parts
- Produces actual injection molded part
- Huge range of production material

Cons:

- Can be limited in features or size capabilities
- Don't always own the tool, just the parts
- Complex parts with slides and action may not be achievable
- Requires tooling
- Changes often require re-tooling

Conclusion:

Initially this process seems like a great alternative to standard hard tooling, however, not all rapid injection molders are set-up to handle very small delicate parts. Extreme features and tolerances might also be challenging if that is an important part of the prototyping phase. Technically speaking this process should be capable of producing many types of small parts.

We could not find a rapid molder willing to take on this part.

k. Standard Micro-Mold® Hard Tooling as Prototyping

As the name suggests standard hard tooling is the process of producing traditional hard steel tooling to injection mold parts. From a prototyping standpoint there are opportunities to shave time and expense out of process by utilizing options such as standard MUD bases, pick-a-part molds or manual action on slides. The process still produces the exact same part a full-production mold would but may give opportunity to speed the process up while reducing cost.

One of the largest benefits to utilize standard Micro-Mold® tooling for prototyping are the insights that are gained by actual representation of mass manufacturing. Other processes might not reveal what the real-life manufacturing requirements may be. For example, machined features do not fill in the same manner when molded. These are lessons that can be learned along with the prototyping process when using this method.

Stated Capabilities:
- Very tight tolerances (2 microns)
- Extremely high repeatability

Pros:
- Very high resolution
- Capable of very high volumes
- Huge range of production material
- Actual production parts and materials
- In-mold (insert molding) process capable
- Final manufacturing process insight

Cons:
- Slower process
- Can be more expensive
- Tooling required
- Changes often require re-tooling

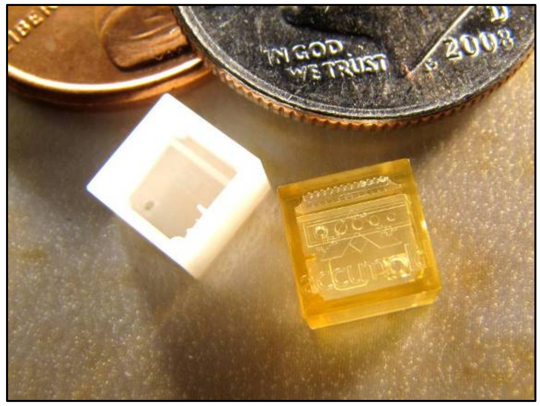

Figure 16

Conclusion:

Standard hard tooling as prototyping is the best method to produce a part to spec, however, it's not really a rapid process when compared to the other available options and it can be more expensive as well.

Micro molded tool and parts produced by Accumold.

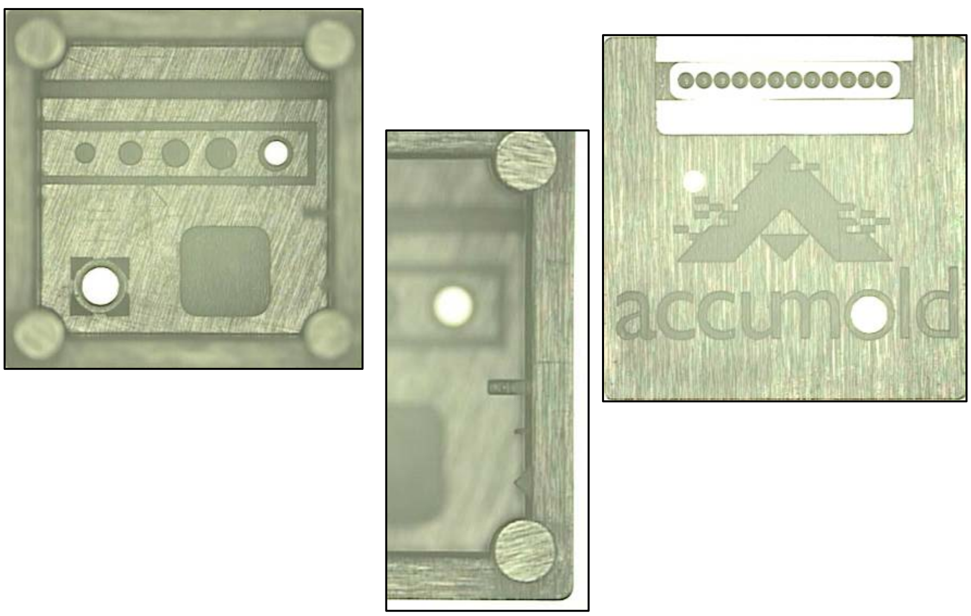

Figure 17

V. Other Considerations

When it comes to introducing new products to the market the requirements of the components that make up the new device can be all over the map. For the most part, these rapid prototyping methods produce one type of "all" plastic part. If your application requires other features such as encapsulation, over molding, insert molding, highly polished surfaces or the like, there might be only one or two options from which to choose. Adding in extreme size, tolerances or complexity only add to the difficulty of prototyping.

As we noted in the beginning of the presentation, new innovation and technology are constantly being imagined. New ways to push the limits of what we know, or break-throughs in areas we never imagined are constantly being realized. For example, several companies are changing what we know about stereolithography and a process known as micro-stereolithography has emerged. This process is capable of resolutions in the microns and will continue to become more commercialized in the near future. [41]

VI. The Conclusion

When it's all said and done each part, each situation, has to be evaluated individually to determine the best prototyping process. Every one of these methods has its place in the process, each with their own strengths and weaknesses to consider.

When looking through the "micro" lens it might require new thinking when it comes to producing micro parts and features. New technology and continually pushing the limits of what we know can open doors, create opportunity and ultimately help make you successful. Because at the end of the day it's all about making good products!

[1] http://www.merriam-webster.com/dictionary/prototype
[2] http://en.wikipedia.org/wiki/Stereolithography
[3] http://www.quickparts.com/english_Quickparts_2.aspx?Page=/LowVolumePrototypes/SLA.aspx
[4] http://en.wikipedia.org/wiki/Chuck_Hull
[5] http://www.protocam.com/html/slapro.html
[6] http://www.protocam.com/html/slapro.html
[7] http://en.wikipedia.org/wiki/Stereolithography
[8] http://rapid-prototyping.harvest-tech.com/stereolithography.htm
[9] http://www.custompartnet.com/wu/ink-jet-printing
[10] http://www.custompartnet.com/wu/ink-jet-printing
[11] http://www.custompartnet.com/wu/ink-jet-printing
[12] http://www.custompartnet.com/wu/ink-jet-printing
[13] http://www.custompartnet.com/wu/ink-jet-printing
[14] http://www.custompartnet.com/wu/ink-jet-printing
[15] http://www.mit.edu/~tdp/whatis3dp.html
[16] http://www.zcorp.com/documents/241_Printer%20Technical%20Specs%20Table%20v2.pdf
[17] http://www.xpress3d.com/Zcorp3DP.aspx
[18] http://www.xpress3d.com/Objet.aspx
[19] http://www.xpress3d.com/Objet.aspx
[20] http://www.objet.com/Products/Connex500/tabid/273/Default.aspx
[21] http://www.objet.com/Products/Connex500/tabid/273/Default.aspx
[22] http://www.objet.com/Products/Connex500/tabid/273/Default.aspx
[23] http://www.rapid3d.com/a_html/rp.html
[24] http://en.wikipedia.org/wiki/Fused_deposition_modeling
[25] http://www.fortus.com/Fortus900mc.aspx
[26] http://www.fortus.com/Fortus900mc.aspx
[27] http://www.stratasys.com/uploadedFiles/North_America/Resources/White_Papers/Files_-_White_Papers/WPGrimm.pdf , p. 2
[28] http://www.3dsystems.com/products/sls/index.asp
[29] http://en.wikipedia.org/wiki/Selective_laser_sintering
[30] http://www.3dsystems.com/products/datafiles/datasheets-1007/SLS/DS-Sinterstation_Pro_US_0407.pdf p.2
[31] http://www.efunda.com/processes/rapid_prototyping/sls.cfm
[32] http://home.att.net/~castleisland/lom_int.htm
[33] http://www.peridotinc.com/urethane-castings.html
[34] http://www.quickparts.com/english_Quickparts_2.aspx?Page=/LowVolumePrototypes/CastUrethanes.aspx
[35] http://www.quickparts.com/english_Quickparts_2.aspx?Page=/LowVolumePrototypes/CastUrethanes.aspx
[36] http://www.quickparts.com/english_Quickparts_2.aspx?Page=/LowVolumePrototypes/CastUrethanes.aspx
[37] http://manufacturing-fabrication.globalspec.com/LearnMore/Part_Fabrication_Production/Machine_Shop_Services/Plastic_Machining_Services
[38] http://microlution-inc.com/products/products.php
[39] http://microlution-inc.com/products/products.php
[40] http://www.protomold.com/ProtomoldProcess.aspx
[41] http://www.mrs.org/s_mrs/sec_subscribe.asp?CID=2587&DID=118531&action=detail

Image Sources:
Figure 1 - http://pchistory.ru/wp-content/uploads/compaq_deskpro_386s_vid.jpg
Figure 2 - http://reviews.cnet.com/sc/31829082-2-440-front+gum-4.gif
Figure 3 - Accumold
Figure 4 - Accumold
Figure 5 - Accumold
Figure 6 - http://www.solid-scape.com/top_services_case_study.pdf
Figure 7 - Accumold
Figure 8 - Accumold
Figure 9 - Accumold
Figure 10 - http://www.fortus.com/uploadedImages/North_America/Media/PCABS_large.jpg
Figure 11 - http://www.selecteng.com/images/slsrose.jpg
Figure 12 - http://www.techok.com/molding-gallery.html#
Figure 13 - Accumold
Figure 14 - Accumold
Figure 15 - http://bunniestudios.com/blog/images/makingchumby/mold1.jpg
Figure 16 - Accumold
Figure 17 - Accumold