Micro Molding Bio-Resorbable Polymers for Medical Devices

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Oct 10, 2012 Rev A DRAFT

Micro Molding in bio-resorbable PLA and PGA materials creates challenges with small gate sizes for these highly shear sensitive and highly moisture sensitive materials. This article dives into some of these challenges such as shear stress through small gates, humidity control for extremely small shot sizes, and integrating macro to micro technologies to produce near micron level geometry in precision, micro molded bio-resorbable components.

As implantable and bio-resorbable molded parts approach micro or nano in size, even a toothpick-sized runner is still too large and too costly. Bio-resorbable raw material costs are between $3,000-$22,000/lb. Within this article is a case study for micro molding with bio-resorbable polymers creating an instant return on investment for molding with net zero material losses in runner and sprue scrap.

Definitions

MICRO MOLDING: Although there is no standard definition of micromolded components in the industry, most micro manufactured components have one or more of the following attributes:

- Fractions of a plastic pellet or weighing fractions of a gram
- Having wall thickness of less than .005”(0.127mm)
- Having tolerances of .0001” to .0002”(0.0025 to .0050mm)
- Having geometry seen only by use of a microscope

BIO-RESORBABLE MATERIAL: Bi-resorbable polymers have been on the market for over 20 years. These polymers are typically PLA based (Poly Lactic Acid) or milk based. They are commonly compounded with PGA called PLA/PGA compounds (Lactide/glycolide). These materials are used in implantable applications when the device is only needed in vitro short term.

INTRINSIC VISCOSITY: Most polymer processing uses melt flow index as an indicator for processability. With BIO-resorbable polymers, an IV (Intrinsic Viscosity) test is used to determine the characterization of the polymer as it relates to Molecular Weight, processability, and in vitro stability. IV is a measure of a polymer’s capability to enhance the viscosity of the solution it lives in. It is important to find the viscosity at different concentrations and extrapolate to zero concentration.

Bio-Resorbable Applications

Figure 1.1 shows common applications for Bio-Resorbable micro molded components. In this life cycle curve, most of the work being done is in the new product area, R&D developments, drug-eluding products, and implants being used as pharmaceutical “carriers”. Growth products in the hundreds of thousands of parts annually are bone screws, anchors, and swallowable pills. Bone screws typically made of Titanium can be replaced with bio-resorbable materials so that patients are not “stuck” with that bone screw for the rest of their lives. The resorbable bone screw, unlike the titanium one, after an approved amount of time, the bone fuses together and no longer required the screw, and the resorbable material then gets absorbed by the body and turns into carbon dioxide and water and is flushed from the human system naturally.

Mature products is also a very busy segment due to what is called “a work around method” whereby conventional molders may be putting micro components into large mold frames and conventionally-sized molding machines. These programs are almost always an

immediate return on investment to re-tool due to the runners and sprues being so very costly in material scrap they generate.

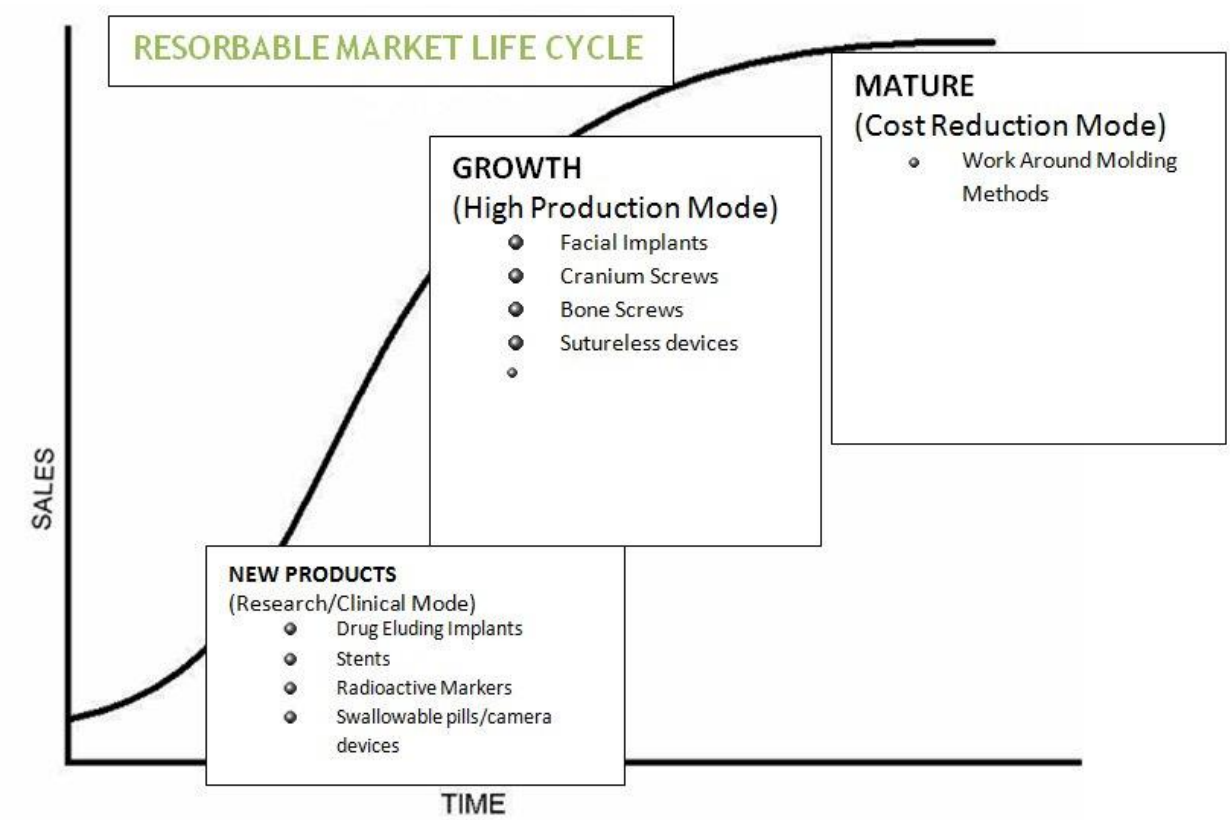

Figure 1.1 MES Bio-Resorbable Market Life Cycle Chart

High volume (Growth) bio-resorbable products are facial implants from reconstructive surgery for aesthetic reasons or accident/disfiguring reasons. Additional high volume products (100k+) are seen in bone screws and sutureless devices such as resorbable sutures, needles, anchors, and staples.

Automation Challenges for Bio-Resorbable High Volume Applications
High volume bio-resorbable components require custom automation and metrology to handle them properly, assemble, and properly package them for many temperature and humidity environments (two things bio-resorbables cannot withstand well).

It is clear to our "tiny" industry that the best way to handle a micro part is to not "handle it" at all. If that mantra is upheld, how do we prepare the parts for assembly and how do we design in a "no handling" process?

WHAT IS IDEAL FOR PART HANDLING AVOIDANCE?
Much ado is being talked about in the micro world about micro factories. One such system was recently seen as a fully functioning cell that fit on a briefcase. These systems, small and compact all work on the premise of NOT handling the micro parts too often or not at all. Micro parts that are created and put down in a bin, bowl, guide, or nest need to be picked up again, re-oriented and re-introduced to the mating component or components next in line for the assembly.

Each step that requires a micro part to be picked up and put back down adds error and given that they are micro parts, there isn't much room for error. A few do options exist however to avoid or at least minimize micro part handling in a micro assembly:

1. Create a micro factory with little tiny machines that enable ONE holding chuck or end-of-arm tool which interfaces with tiny micro mills, micro molders, micro stamping stations, etc. to create a final micro assembly all within the size of a cereal box.
2. Combine geometry (stealing from Peter to pay Paul) in as few steps as possible (i.e.valve/pump combinations, valve/chip combinations, insert micro molding, in-mold micro assembly, 6-axis micro machining with indexing station).

MICRO ASSEMBLY ENVIRONMENT REQUIREMENTS?

Let's face it, we've all seen our parts flick, stick, fly, fall, dive, tweak, and bounce all over the place at one point in time. We learned that valuable lesson of static elimination, the wonders of de-ionized air, and the criticality of temperature and humidity control in our environment. Under a polycarbonate transparent screen inside an automation cell, these conditions are heightened.

Laser welders, heat, parts riding on guides, metallic parts turning in vibratory bowls all create an environment not befitting of micro assembly. We MUST plan for static elimination and cleanliness to keep the dust from being disguised as our micro assembly somewhere down the line. It is especially important for Classified and Certified Cleanrooms to be installed via Hepa filtration systems in micro automation/assembly systems.

WHAT TYPE OF QUALITY DO I NEED FOR MY MICRO PARTS TO FUNCTION IN FINAL ASSEMBLY?

As parts get assembled into sub-assemblies and final assemblies, the cost to scrap them escalates significantly. It is therefore important to consider the flow chart of an automated assembly cell that may require orienting parts to avoid gates, protrusions, wall thickness anomalies, etc. The cost to scrap an assembly is much higher as each micro part is added to the assembly automation system. For this reason, we identify and plan for parts' anomalies and at each station how that anomaly will be positioned and properly oriented in the sub-assembly.

There are ways in determining what tolerances each part needs to have in order for their incremental or stack-up tolerances in the final assembly. This is called a tolerance study. This is a critical piece of the micro device assembly and automation system. It is recommended that a detailed tolerance analysis is performed using +/- 6 sigma statistical tolerances (Max and Min) such that a micro assembly can be planned and executed with quantifiable and reasonable tolerances per part in the assembly. There are several software packages that aid in this process but as with any tool, it is important to understand the nuances in each micro process that will feed the correct information into this study to get the desired and correct result.

Processing Challenges of Bio-Resorbables

There are many different compounds of PLA/PGA. A common grade is the 82/18 version (82% lactide, 18% glycolide). A very high concentration of glycolide creates material handling and feeding difficulties due to "gooey" nature of the glycolide.

An abundance of information can be found using several of the bio-resorbable polymer suppliers (Purac, Evonik, Lakeshore, DSM to name a few). When it comes to micro molding,

however little or no information is available on the market due to proprietary processing techniques and lack of industry-specific testing for custom compounds.

The first challenge encountered by processors of bio-resorbables is material handling, which is the single largest area for error. PLA/PGA materials are highly susceptible to moisture and heat. They must be stored properly (usually in a freezer) at a specified temperature in nitrogen-sealed foil pouches. They must then be used according to the processing run quantities needed and material drying cycle. The material usage must be matched with the injection screw and shot size in an injection molding machine so that the material is not sitting in an improperly sized machine where over-drying and over-heating can occur due to the prolonged temperature and drying exposure.

Many material and processing platforms are used for bio-resorbable assemblies. Each of these have nuances to consider in automated assembly. Here are a few examples:

1. ***Molded Parts***- Great choice for economic assembly and high volume production! However, there are some nuances that you have to consider with micro molded parts whether they are thermoplastic, silicone, or metal injection molded.
    a. RUNNER/SPRUE- The runner and/or sprue (if one exists), can be our friend or foe in micro assembly. We could use it as part of an assembly aid to hold onto a part in the automated assembly or add special locating "jogs" in the runner aid in the positioning in an assembly nest.
    b. PARTING LINES- Molded halves come together and form parting lines on molded parts on the order of ~0.0002-0.0003" (~ 10 microns). These parting lines need to be considered when they will be assembled to other parts, they can prevent proper fit if they are not "guided" or moved through the assembly process properly. These 10 microns can easily make or break your assembly.
    c. DRAFT- It's not much with micro molded parts, sometimes as small as 0.2 degree of taper but this taper (inside or outside) of a molded part can be cumbersome to deal with. Having your micro part "ride" on a taper will provide an arbitrary or irregular surface with which to improperly position it for assembly to other parts. Ways around this are to eliminate draft on a small portion of the part being positioned, draft the assembly station/fixture with the matching draft angle, or add a feature to the part or runner that can be used and removed later on. (see above runner/sprue)
    d. GATE LOCATION- As micro molders it's critical to choose a gate location that will actually create uniform flow in a micro molded part. Without a uniform flow, the part may not fill the mold and do damage to the delicate pins and cavities we took such care in creating. We ARE thinking ahead as to how we are going to remove this gate later on in the assembly process. (see below) but the location is important because if it has already been de-gated, the gate trim job may have left a divot or a proud protrusion that has to be rotated away from nesting, guide rails, or other parts.
    e. GATE VESTIGE- Most micro molded parts are kept on an edge gate. If so, they need to be de-gated properly to avoid issues with small "picks" of material causing damage to an artery, or causing issues with automation and assembly. These small picks can be addressed in the mold design by placing a dimple in the wall thickness (if the walls are thick enough that is) so the vestige will "sit" below the surface of a guide or a mating component in the assembly.

f. SURFACE FINISH- Often overlooked, the surface finish of a molded part is important in "riding" or "guiding" features into other features. Some surface finishes in assembly are best served with vapor honing or roughening the surface to provide improved surface area for bonding, for example. Smoother surfaces in assembly can cause problems in ejection from the mold and a trade-off surface may be required in order to "steal from Peter to pay Paul". Which one will be the lesser of the two evils is dependent on material selection (see above)

Bio-Resorbable Micro Mold Design
A mold design with a properly sized gate and a very small runner and sprue (if any) is critical to product quality and cost. Bio-resorbable raw material costs are between $3,000-$22,000/lb and even a toothpick-sized runner and sprue adds up to hundreds of thousands of dollars of scrap annually.

Mold venting is also important as clogged vents will also degrade the polymer prematurely and cause burning of the implant during processing.

If gates and runners are used, a micro molded part is typically easier to degate using an edge gate vs. a sub gate. Degating methods such as ultrasonic degating, tiny knives in a fixture, or in-mold degating are used to avoid this effect. If the bio-resorbable implant is in direct contact with skin or arteries, even a very small gate vestige is detrimental to the implantable application as that picky piece can pierce an artery or vein. If the wall thickness allows, cutting into the part vs. leaving a small vestige is better than chancing the vestige. (+0.00/-0.05mm is typical)

INJECTION MOLDING PROCESS

The tooling (mold) is truly the enabler to manufacturing bio-resorbable components, and then there's the micro injection molding process which needs to get you the remaining 10% to the finish line. With micro molded parts and features in the single digit micron range, there are several challenges that must be overcome to achieve tool to molded part replication. It is one thing to make nice sharp corners and cavities in steel (less than 1 micron radii) but it quite another to FILL those tiny spaces with polymer. Proper venting is required, sometimes with extremely thin laminates (puzzle pieces of steel) to achieve proper degassing and therefore filling of sharp corners to replicate steel to polymer corners.

Properly sized machines – It's very common to see micromolded components that have sprue and runner systems amount to 75% or more of the total shot. For many molders trying to enter this market, micromolding parts in larger machines is commonly attempted.

Molding parts in this manner is not recommended on machines larger than 0.5 ounce because it is hard to control such small shot sizes. Also, long residence times and material degradation would occur with oversize screw and barrel combinations. Tabletop machines are not considered good candidates for micromolding, as they are not usually designed for high-volume production and process control capability.

Micro molding machines are also a key component to processing resorbable polymers. Because they are highly shear and heat sensitive, proper fit of the shot size to the screw and barrel is critical. The residence time (time the polymer sits in the barrel) can affect the IV of the material. Small shot sized machines are typical in the design of micro molding machines. Some machines used reciprocating screws and some use screw over plunger

technology. A partial view of commercially available micro injection units are seen in Figure 1.3. Some other machines are being developed by processors of resorbable materials because even the smallest shot sizes available on the market are too large to properly process small amounts of resorbable polymers. These machines are typically proprietary and primarily uses internally or through licensing agreements.

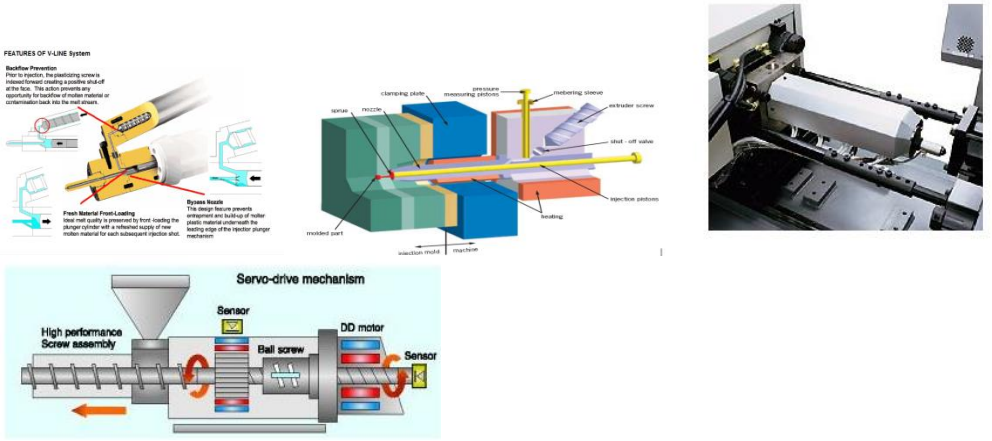

Figure 1.3-Sodick, Battenfeld, Nissei, Sumitomo Micro Injection Units

Typical injection pressures in micro molded parts are upwards of 30,000-50,000 psi which requires a balancing act of injection pressure to holding onto tiny core pins so they don't flail around in the breeze. Dust specked size parts with extremely thin walls (0.001-0.0015") require extreme cavity to core alignment across parting lines. This allows the polymer to flow balanced throughout the injection molding process without freezing off. If the polymer freezes off in a non-fill condition OR if the part fills more on one side than another (imbalanced flow) it is likely that micro mold core pin damage will occur. This challenge is overcome with fast injection times (typically < 0.1 sec) and high injection pressures (30k-40k psi). With these two variables, it is clear that the tool must be robust and highly precise to meet these challenges in injection mold filling.

Figure 1.4 shows a partial listing of micro molding machines. This list is quite expanded, however the equipment manufacturers are still primarily the same. There are triple the amount of micro molding machines on the market now than back then, speaking volumes for the number of micro molding applications required worldwide. Micro molding machines must have the capability of injecting very small shot sizes as to keep the residence time in the barrel to a minimum. This is especially important for bioresorbable polymers (PLA, PLGA) which are highly shear and heat sensitive. Specialized screws, nozzles, and auxiliary equipment are also needed to provide the level of precision of filling, handling, degating, measuring, and assembling these tiny devices.

Partial List of Micro Molding Machines

	Battenfeld	Boy	Ferromatik Milacron	Juken	Medical Murray	Nissei	Nissei	Nissei	Sodick	Sumitomo	Toshiba
Model	Microsystem	Boy 12S-11	Babyplast	0155-5t	0.08	HM7-C	HM7 Denkey	AUS	TR10S3	SE10S	ECS-0.1A
Tonnage	5.6	3.1	6.6	5	1	7	7	3	10	10	5.5
Injection Capacity (oz)	0.04	0.21	0.13	0.17	0.0028	0.21	0.21	0.11	0.5	0.21	0.24
Injection Capacity (cm3)	1.1	6.1	3.8	5	0.08	6.2	6.2	3.1	14	6.2	7.1
Injection Psi	36,259	26,106	38,425	19,290	50,763	25,388	25,600		0.47	32,429	29,000
Screw Diameter (in)	0.55	0.55		0.63		0.55	0.55	0.55	0.7	0.55	0.55
Inj Piston Dia (in)	0.197	n/a	n/a	n/a	0.063	n/a	n/a	0.47	0.6	n/a	n/a
Max Daylight (in)	11.8	11.8	5.51	9		8.7	8.7		14.6		9.8
Dry Cycle Time (sec)	1.5		2.4			2	2	2			1.9
Min Mold Height (in)	3.97		1.18		3.2	4.3	4.3	3.15	5.9	5.1	4.53
Max Clamp Stroke (in)	7.87		4.33	4.59	5.9	4.3	4.3	3.15	8.7	6.3	5.3
Max Mold Size (in)	7.72 x 6.14		2.95 x 2.95	3.9 x 3.9	4 x 4	3.5x3.5	5.5x5.5	6.7x6.3	9.5x9.5		8.7 x 8.7
Tie Bar Spacing (in)		10 x 10	3 x 3		4.4 x 4.4	4 x 4	6.5	6.88	10.2x10.2	9.3 x 9.3	Tie Bar Less
Ejector Stroke (in)	1.18	1.18	1.77	1.18			0.79		2	1.96	1.2
Footprint-LWH (in)	73x81x95	90x38x63	35x18x26	53x30x78			68x24x63	54x20x61	95x32x72	89x24x57	71x31x55

Figure 1.4 Partial List of Micro Molding Machines

Attention to detail for micro components at the design stage carry through to automated assembly. Because the tolerances are critical and diminishing to microns and sub-microns, the stack-up tolerances of the micro components and their design criteria must be scrutinized and their method of manufacturing also considered for long-term production.

PROCESSING

Micro molding machines are also a key component to processing bio-resorbable polymers. Because they are highly shear and heat sensitive, proper fit of the shot size for a micro molded part to the screw and barrel is critical. The residence time (time the polymer sits in the barrel) can affect the IV (Intrinsic Viscosity) of the material. Small shot sized machines are typical in the design of micro molding machines.

Some machines used reciprocating screws and some use screw over plunger technology. Some other machines are being developed by processors of bio-resorbable materials because even the smallest shot sizes available on the market are too large to properly process small amounts of bio-resorbable polymers.

These machines are typically proprietary and primarily uses internally or through licensing agreements.

Many challenges exist in micromolding but there are ways to minimize these challenges and corresponding risk of failure to component manufacturers. Some of these challenges include:

Modeling of Micro Components – There remains a limited understanding of the fundamental physics at the micro scale, which are necessary to develop reliable models. Perfecting the mesh is critical to obtaining the correct result in any analysis. Because micro parts have such small features (and therefore very large solid model sizes), painstaking processes in meshing a very high resolution model is key to an accurate analysis.

Environment – As a fraction of one single degree of temperature change can affect precision when machining (or measuring) at the submicron level, many micromolders and micro machining experts enclose the entire machine and/or inspection area in order to create a controlled working environment.

Metrology/Inspection Techniques – Inspection techniques in measuring very small micromolded parts requires customized vises, tweezers, and fixturing (not to mention extreme patience). Inspecting steel measurements usually provides a flat, robust surface that can be measured with non-contact means or in some cases contact measurement. These same surfaces that make the molded components can be used to "certify" the dimensions much closer in repeatability and reproducibility than attempting the same corresponding measurement in the micromolded components. It's not uncommon for the first article inspection to consume as much time if not more time than the entire micro moldmaking and micromolding project combined. One of the latest time saving techniques in this area, however is laser scanning of the micro part which scans the part, turns it into a point cloud data, and that data can then be directly file compared to the nominal solid model to see visually in color where problem dimensions exist.

Gage R&R from client to vendor requires duplicate fixtures and exact methods of inspection technique to repeat the results to near micron tolerances. Only a select few sources of inspection equipment exist that are capable of measuring to sub-micron tolerances and extremely clean and hepa-filtered, air controlled rooms are necessary to the environment needed for repeatable measurements.

It's also common in macro components and specifically with medical devices to insist on 1.33 Cpk or better with respect to performance to drawing dimensions or tolerance. 1.33 Cpk on .0001" tolerances requires nearly a mathematical impossibility in some cases when the gage R&R and operator R&R are taken into account. Component manufacturers and micromolders require similar inspection machines with identical fixtures to validate tolerances in micro components.

Part Handling/Static – Part handling can be challenging given the sizes of micromolded components. Many micromolders use edge-gated runners to carry their parts from one location to another and many are used as part of the automation process. If parts cannot be edge-gated, customized end of arm tooling, vacuum systems, reel-to-reel take-up equipment and blister packs are utilized accordingly.

Static electricity is a micromolders nightmare. Parts as small as dust can easily be lost if proper grounding of part collection systems, robotics, packaging, and inspection systems are not performed. Static guns, wands, air curtains, and grounding mats are commonplace in micromolding facilities.

MATERIALS TESTING

In order to determine if the bio-resorbable implant is robust enough, it is important to characterize the material during many different phases in the injection molding process. For example, PLA/PGA pellets in their raw form are stored in nitrogen sealed pouches. Opening this pouch and exposing the polymer to a small degree of temperature and humidity starts

to degrade the polymer immediately. (as if it were in the body already and starting to do its job).

Consequently PLA/PGA compounds must be dried in nitrogen sealed hoppers in most cases and IV's must be validated throughout the injection molding process. Temperature from shear in the injection molding screw and barrel temperatures also decrease the materials IV. Additional shear from small mold gates are also a source for decreasing the IV. Once the PLA/PGA component is molded, however it has a protective skin around the molded part and can be left for a small period of time outside of a nitrogen-sealed environment.

VALIDATION:
Due to the nature of bio-resorbable polymers and their use in implantable devices, they are often processed in a classified cleanroom and be validated using ISO 9001 and/or under ISO 13485 quality systems.

Throughout the molding process, Intrinsic Viscosity values should be validated. Samples should be taken from the bag, after the drying process, after the molding cycle by testing both the runner and the part to compare shear effects through the gates, and after a period of time in the package, and through different temperatures for shelf life tests.

This testing will insure the validity of the implant throughout its living cycle in vitro for properly form, fit and function of the implantable device.

DESIGN OF EXPERIMENT/TESTING
By the time a 4.0 IV material is processed, rapid deterioration of polymer properties can take place. If improperly processed, the material will "act" improperly in vitro and cause an implant to resorb prematurely. There are tools available to test the impact of processing conditions on PLA/PGA materials. One of these tools is a gate shear test and tensile bar test shown in Figure 1.4. The gate shear test is 8 cavities with varying wall thickness from .002" to .009" (0.05-0.23mm) and the gate is always 75% of the wall thickness. The varying gates will simulate varying shear on the PLA/PGA materials. These "coupons" are then tested for IV loss and simulate what happens to a particular compound before an expensive shaped mold is built using a similar gate size. The tensile bar, an ASTM standard for micro molding, can be used to test tensile properties of a given wall thickness.


Figure 1.4 Spiral Flow Test and Micro Tensile Test Bars

CASE STUDY
Mature products, although not truly mature in time years, but mature in cost and depreciation are seen when conventional injection molding methods are used to create the molded parts. This is typical when using 40Ton-80Ton presses which require larger surface area molds to fit in them. The material loss due to large paths in sprues and runners are extremely costly for $3,000/lb materials. These mature products always return on their initial investment to transfer to a micro molding sized mold and return even quicker with a runnerless mold.

The following example in Figure 1.5 shows a typical ROI for what is referred to as a "work around" conventional method to a micro molding method. $4,000,000.00 in cost savings is realized when changing from a toothpick-sized runner and sprue to a runnerless bio-resorbable mold. It would take just one molding run to pay for the capital of micro runnerless tooling/molding machine. This is a Controller's dream and what is commonly referred to in the industry as a "no-brainer".

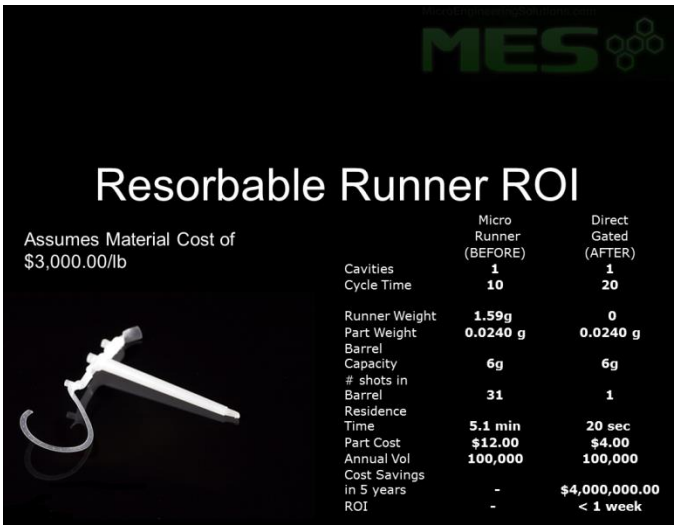

Figure 1.5-Typical Bio-Resorbable Product ROI- Conventional molding vs. Micro molding approach

Conclusion

In conclusion, there are critical steps required to handling, testing, processing, assembling, and validating bio-resorbable components. Material characterization throughout the process is critical to understand what happens to the Intrinsic Viscosity of bio-resorbable polymers such that when they are in the body, they will not prematurely resorb OR stay too long for the implant to properly function.

As is usually the case in micro molding, this type of processing requires specialized equipment, design, and validation expertise. Choosing the right supplier and one that is experienced in bio-resorbable processing and micro feature generation will create a faster path to success.

Donna Bibber is a Plastics Engineer with 25 years of experience in micro manufacturing. Ms. Bibber has written and lectured hundreds of technical papers on micro and ultra-precision manufacturing associated topics worldwide and was voted onto the List of 100 Notable People in Medical Devices.