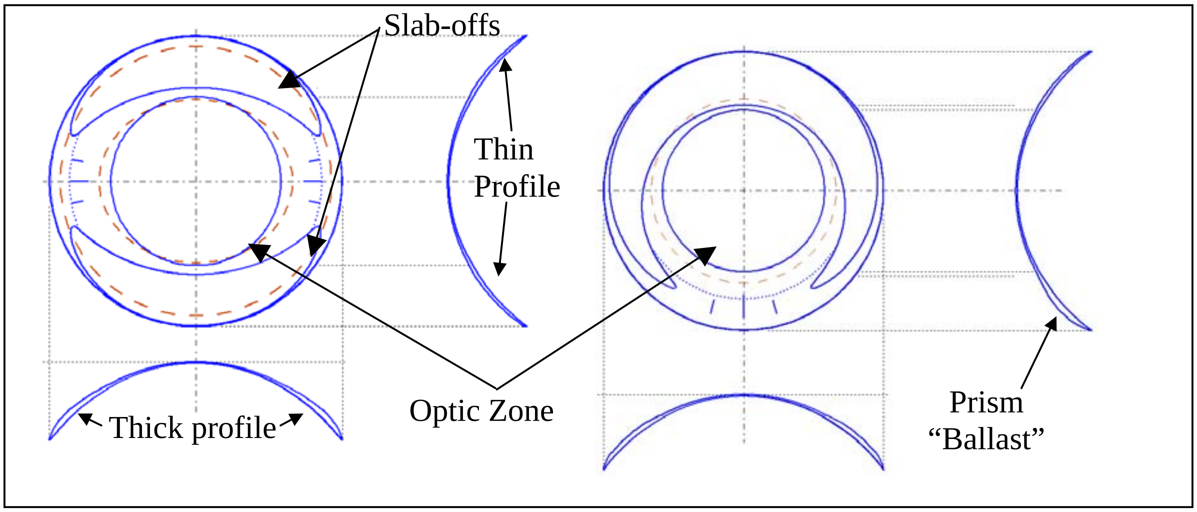
Need for Precision Engineering in Astigmatic Contact Lenses

Matias Heinrich, Chris Wildsmith
Vistakon, J&J Vision Care, Inc., Jacksonville, FL

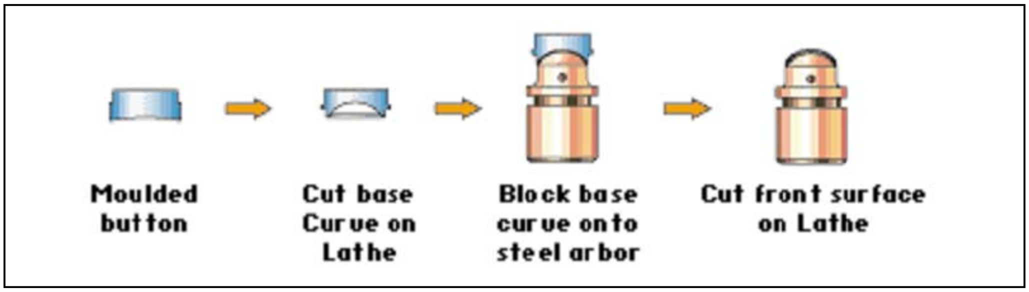
The Design, Manufacture and Metrology of contact lenses is a field heavily dependent on the existence and advancement of Precision Engineering. Astigmatic lenses (also called torics) are used to correct vision when the ocular system needs one power of correction along one direction (axis) and a different power along another. In Astigmatic lenses, the two powers are generally orthogonal to each other and the corrective lens must be held in place to prohibit excessive angular rotation thereby keeping the respective powers in the proper angular orientation. On astigmatic lenses, and other higher order aberration lenses, the central 4 to 8 mm contains the power correction (also known as the Optic Zone, or OZ) and all, or part of the remaining portion of the lens, provides the angular stabilization (Stabilization Zones). Stabilization zones use gravity and/or blinking forces of the eye to hold the lens in place. Solid modeling and the mating of dynamic FEA taking into account variables such as tear film thickness, viscosity and the velocity and direction of eyelid movement, have opened new avenues to design procurement. Contact lenses for correcting astigmatism can have a back surface toric, a front surface toric, or both, but all types all need stabilization zones.



Toric Contact Lens Designs with Double Slab-off (left) and Prism Ballast (right) Stabilization.

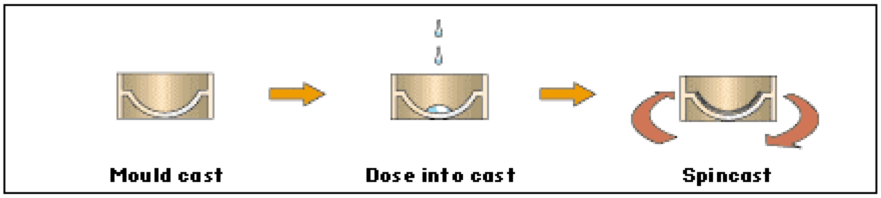
Manufacturing

Manufacturing techniques of contact lenses include spin casting, cast molding, and direct lathing of contact lens material (un-hydrated state) known as buttons. In direct lathing, the base curve (concave) side is machined first. The button is then mounted, using wax, on to an arbor that has a profile similar to the base curve as seen in the figure below. Once the wax has hardened, the front surface is machined. The toric optic zone can be achieved either by a toric generator, or by crimping (pinching) a button while on the arbor and machining a spherical optic zone. When the crimped button is released, a toric surface remains.



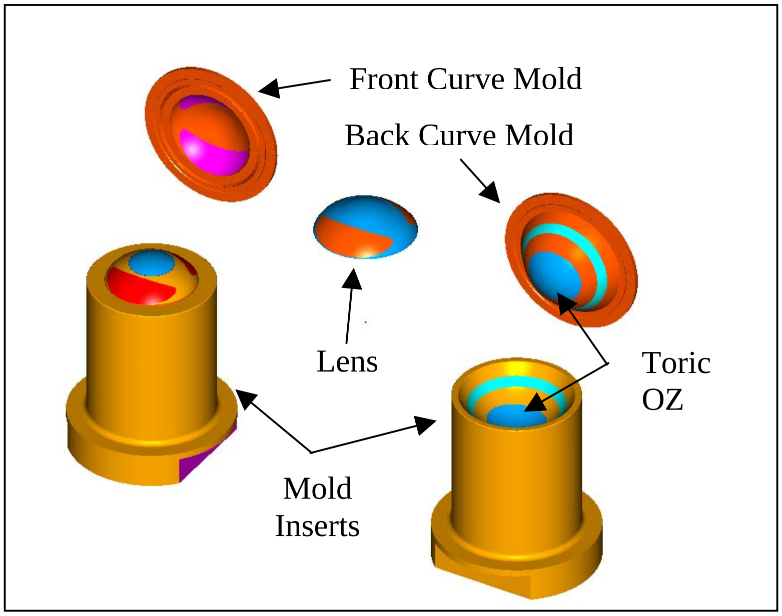
Principle of Direct Lathing of Contact Lens

Spin casting generally utilizes one mold and liquid monomer. Front surface spin cast toric lenses can be produced by machining a concave surface (containing the stabilization and toric OZ), and dosing this cast with monomer. The cast is rotated and curing of the monomer induced to produce an unhydrated lens. The toric optic zone and stabilization can be achieved by either fly-cutting or diamond point turning. This mold can either be turned directly, or injection molded from molds.



Principle of Spin Casting Contact Lens

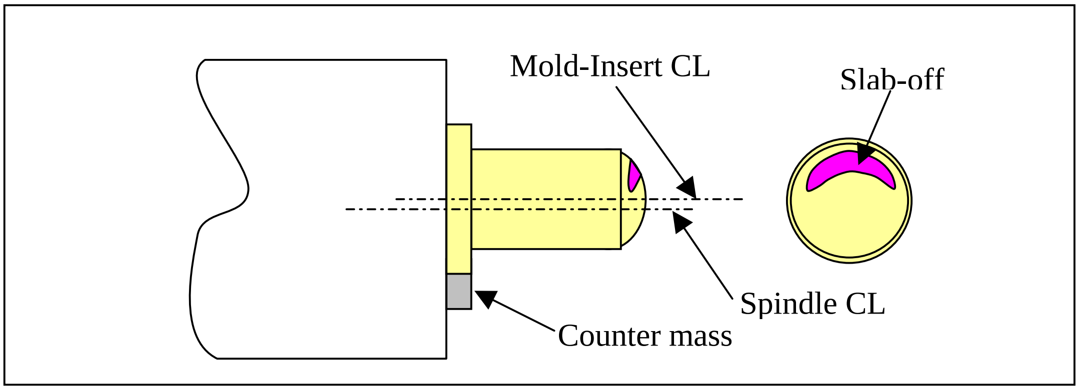
Cast Molding utilizes front and back curve molds that are either directly machined or injection molded from molds. The figure below shows components of a typical cast molding system including injection molding components (mold inserts), plastic cast molds (front and back curve molds), a toric lens with slab-off type stabilization on the front, and the toric optic zone cut into a concave mold-block insert.



Example of Cast Molding Components including Lens, Front and Back Molds and Mold Insert Components

Lenses manufactured from these processes are later hydrated where they absorb 20%-70% water by mass. In spin casting and cast molding, lenses remain in the concave molds after curing. Hydration makes the lenses grow and induces shearing, causing the lenses to separate from the molds.

Slab-off type stabilization can be achieved by fly-cutting, diamond point turning with a tool servo, or offsetting the mold-block insert radially in a diamond turning machine spindle. Running a normal cutting routine and following a rotationally symmetric arc removes material leaving a half-moon shaped depression as seen in the figure below. The amount of radial offset and the radius of the arc drives the size and slope change of the feature.



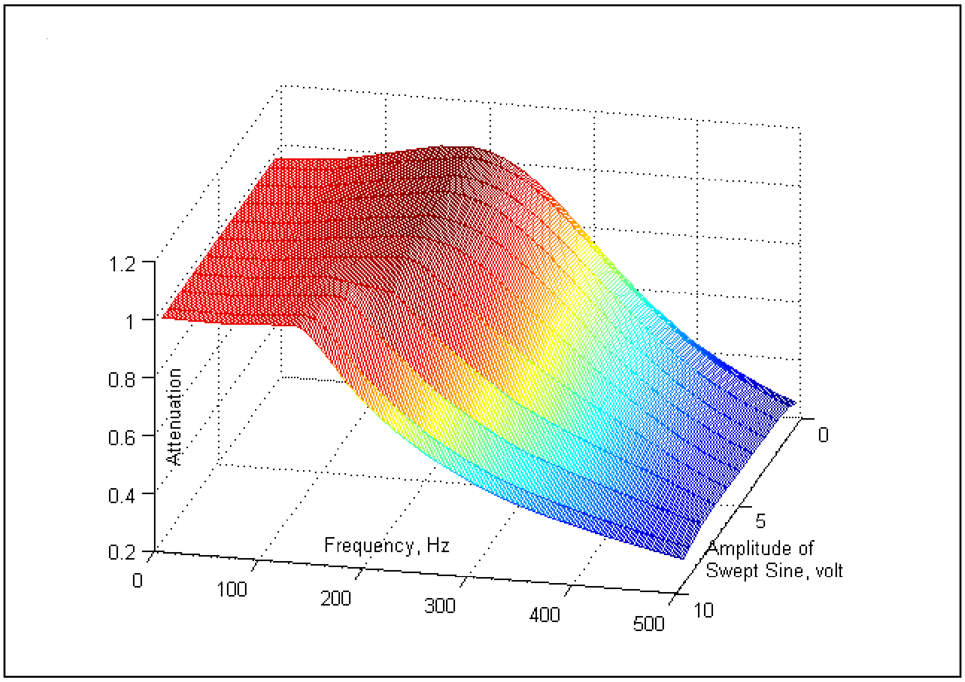
Method of Cutting Slab-offs by Offsetting the Work Piece Radially from the Spindle Centerline and Following a Rotationally Symmetric Tool Path

Slab-offs, when transferred to the lens mold and then to the lens, create a higher slope and thinner region on the lens. By having two of these features on a lens, the natural blinking of the eye pinches the lens and creates a force vector to orient the lens in both the azimuthal and radial directions. The same features can be machined on the lens in a direct lathing process. One draw back to slab-off's is the discontinuity created at the edge of the feature. This sharp junction can cause some discomfort to the eye-lid of the patient. The cast molding process provides local averaging of the surface helping to increase the edge radius of the discontinuity and improving comfort over direct lathing of slab-offs.

Most new freeform machining techniques for contact lens manufacture utilize a tool servo. Tool servos provided a way to eliminate re-fixturing of the work-piece for either slab-offs or toric optic zones.

What is not well understood are the machining envelopes of many commercially available tool servos. Tools are needed to compare design wave-forms to dynamic capability insuring the systems can accurately produce designs. For example, it would be useful if lathe operators and engineers had feedback as to the machineability of a profile and suggestions from the lathe for appropriate machining parameters. Some commercially available systems currently offer a closed-loop feedback feature such as the Slow Slide Servo option offered in the Moore Nanotechnology 220 UPL and 350 UPL. In these systems, spindle speed is constantly adjusted such that slide motion stays within the available dynamic envelope. The disadvantage of the Moore systems, while smoothly integrated into the control system, is the large moving mass of the axes being oscillated. Also a performance monitor should track following error and issue warnings when following errors are too large or system performance is not as expected. The benefits of a well integrated and understood tool servo are quantified part quality such as RMS error over the machined profile, system performance during and after each cycle, and increased through-put.

Some development is now being done to pre-distort tool servo wave-forms such that phase-lag and attenuation are compensated offline in a type of feed-forward compensation. The Precision Engineering Center at North Carolina State University has been working on similar techniques with the aid of dual piezoelectric stack tool servo marketed as the Variform. The widely used Variform has a feed forward analog control system relying on an LVDT position feedback sensor. Recent work at the Center has mapped a frequency response map with an added amplitude dimension. This data becomes very valuable when pre-distorting design files but can also provide boundaries in design filtering routines.

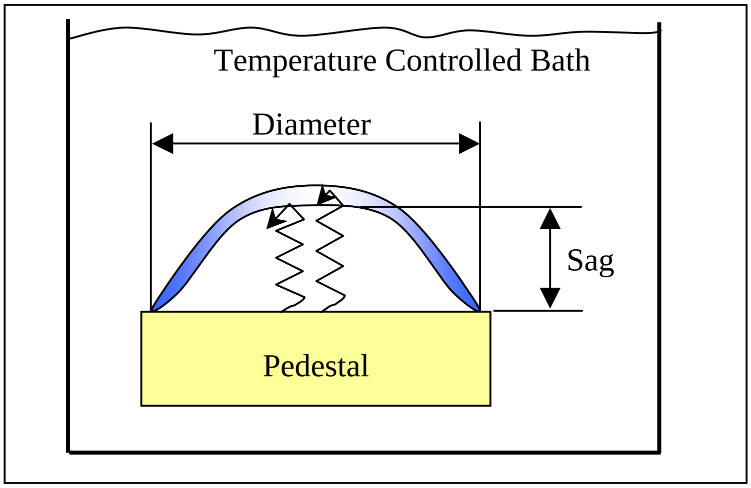


Frequency Response Map a Varying Amplitudes (0-10 Volts).
Courtesy of the Precision Engineering Center, North Carolina State University.

Metrology

Metrology for contact lens manufacture can be broken down into hard state metrology (molds, direct lathed un-hydrated material), or soft state metrology (hydrated lens). Techniques and equipment for hard state metrology are readily available and include Laser Interferometry for Optic Zones (spherical, toric, and some more complex surfaces). The relatively large changes in slope of stabilization zones make X-Y and R-θ profilometry more suitable Stabilization Zones however they are time consuming and usually not fit for production environments. CMM technology is also applicable but tends to be too time consuming for production environments.

One challenge with soft state metrology is having to work with a wet, floppy specimen. A hydrated lens placed in air will immediately begin to dehydrate and deform and so to measure the lens properly, it must be analyzed in a controlled bath with temperatures similar to that of the human eye. Soft state metrology for lenses has historically been limited to a Focimeter to measure the power of the lens. New systems can map the power of the lenses and the corresponding wave-front shift. Stabilization of lenses is also difficult to measure, with cross sectioning being the common method to compare design profiles to actual lens profiles. This is done at a very painstaking pace. Acoustic systems can be used to measure sag and center thickness of a lens as seen the figure below. Equivalent radius on the concave side of the lens can be calculated using the sag measurement and diameter of a lens. Some advances have been made but better means of soft state metrology are still needed.



Acoustic System for measuring Center Thickness and Sag. Equivalent Radius of the Back Surface can be Calculated from the Diameter and Sag.

Conclusion

Contact lens development is a multi-discipline field that builds on precision engineering principles. New freeform machining systems have recently been developed but as an end-user, tools to evaluate manufacturability and compensation for system dynamics as well as real-time process feedback are still required. Toric contact lenses are only the beginning of freeform machining and lenses are being produced for patients that have significant complex wave-front aberrations.