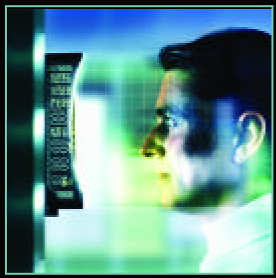
Pushing the Polymer Envelope

White Paper





SYNTEC
TECHNOLOGIES

ABSTRACT

The pressure to "push the polymer envelope" is clear, given the exploding range of demanding applications with optical components. There are two keys to success:

1. Expanded range of polymers with suitable optical properties
2. Sophisticated manufacturing process options with an overall system perspective:
   - Tolerances and costs established relative to need (proof-of-concept, prototype, low to high volume production).
   - Designed to integrate into an assembly that meets all environmental constraints, not just size and weight, which are natural polymer advantages. (Withstanding extreme temperatures and chemical exposure is often critical, as are easy clean-up and general resistance to surface damage.)
   - Highly repeatable.

The thesis of this paper is that systematically innovating processes we already understand on materials we already know can deliver big returns. To illustrate, we introduce HRDT[1]. High Refraction Diamond Turning, a patent-pending processing option to significantly reduce total costs for high index, high thermal applications.

CONTENTS

[1] HRDT (patent pending) and High Refraction Diamond Turning are trademarks of Syntec Technologies, Inc. All other marks are the property of their respective owners.

Materials and Processing: Setting the Stage

Given the widespread use of polymers, it's easy to forget the entire industry is less than 150 years old. Nearly everything about these materials and where they can be used has changed dramatically from those early days and continues to evolve rapidly. You can see this most clearly in optical applications, which have expanded from toys and eyeglasses to advanced blood analyzers, disposable diagnostic cameras, guided weapons systems, head-mounted GPS solutions, sophisticated office and industrial equipment, high performance electronics, and a host of biometric and telecommunication uses. The best of these applications do more than replace glass components with polymer ones; they provide new solutions to previously intractable problems, such as one-time use without expensive sterilization, or reusing the same components in very different packaging.

While cost and malleability remain important polymer hallmarks, the real keys to continued polymer optics expansion are the specific characteristics of available materials and the sophistication of manufacturing processes in implementing designs. The drivers are the relentless need to integrate more and more components into smaller, lighter packaging, at lower cost and higher quality with a wider range of optical spectrums (IR and UV) and environmental resistance (higher heat, increased thermal stability).

Material trends

Figure 1 is a timeline of the major modern optical polymers and their impact.

1936	1940	1960s	1983	Early	Late 1990s
Acrylic or polymethyl methacrylate (PMMA); first optical lenses are made for ophthalmic applications.	WWII sees extensive use of acrylic for aircraft canopies and lightweight window applications.	Kodak introduces plastic optics in low cost fixed focus cameras with PMMA and polystyrene (PS).	Optical grade polycarbonate is widely introduced for ophthalmic lenses, safety glasses, and firemen's shields.	Polyetherimides (PEI) and poly-ethersulfones (PES) are recognized as excellent near IR transmitters with high heat tolerance, perfect for the newly exploding telecom market.	Cyclic olefins provide excellent low moisture absorption substitute for PMMA, with greater thermal stability.

Figure 1. Major introductions of common polymers

Advances in polymer materials stagnated for many years until breakthroughs in the 1990s greatly expanded the options for temperature ranges, transmission quality and stability of the index of refraction. This has given us many more ways to address particular application needs.

For example, polyetherimides and polyethersulfones are now available in optical grades. These plastics exhibit higher transmission quality than previously possible in the near-IR region and withstand operating temperatures from below zero to above 200°C. Several grades of acrylic also deliver relatively high transmission quality from 390 to 1600 nm, with improved temperature operating ranges to minimize the dN/dT (shift of index with respect to temperature) and general thermal stability. Finally, current cyclic olefin products feature extremely low moisture absorption. The issues of moisture absorption and thermal expansion relate directly to the stability of the index of refraction shift with respect to temperature. Each type of polymer has an increasing number of grades available that affect important characteristics such as flow, purity and environmental durability.

Birefringence, where light separates into two diverging beams as it passes through a doubly refracting optic, is not related to any specific material but remains an important material consideration. It can have disastrous effects on polymer systems that are sensitive to polarization. Because birefringence effects are process-driven, materials with higher flow rates are less susceptible. Component design is also a factor in reducing birefringence. When molding components, the harder a component is to fill (which requires more injection pressure) or pack (more holding pressure), the more likely the occurrence of birefringence, although several post molding operations can be implemented to reduce its effects. If, instead of molding, the components are manufactured using diamond turning, birefringence is usually not an issue.

	Unit	PMMA	Poly-styrene	Polyether-imide	Poly-carbonate	Methyl-pentene	ABS	Cyclic Olefin Polymer	Nylon	NAS	SAN
Trade Name		Plexiglas	Styron	Ultem	Lexan	TPX	Acrylon	Zeonex	Polyamide	Methyl	Styrene Acrylonitrile
Refractive Index nf (486.1 nm)		1.497	1.604	1.689	1.593	1.473		1.537		1.575	1.578
Refractive Index nd (589 nm)		1.491	1.590	1.682	1.586	1.467	1.538	1.530	1.535	1.533–1.567	1.567–1.571
Refractive Index nc (656.3 nm)		1.489	1.585	1.653	1.580	1.464		1.527		1.558	1.563
Abbe Value Vd		57.2	30.8	18.94	34	51.9		55.8		35	37.8
Transmission	%[1]	92–95	87–92	82	85–91	90	79–90.6[2]	90–92	88	90	88
Max Continuous Service Temp.	°F °C	161 72	180 82	338 170	255 124			253 123	179.6 82	199.4 93	174–190 79–88
Water Absorption	%[3]	0.3	0.2	0.25	0.15			<0.01	3.3	0.15	0.2–0.35
Haze	%	1–2	2–3		1–3	5	12	1–2	7	3	3
dN/dT	$x10^{-5}$/ºC	–8.5	–12.0		–11.8–14.3			–8.0		–14.0	–11.0
Key Advantages		High transmission & purity Scratch resistance Chemical resistance High Abbe value Low dispersion High melt flow	High index Clarity	Impact resistance Thermal & chemical resistance High index	Impact strength Temperature resistance	Chemical resistance	Durable	Low moisture absorption High transmission & purity Good thermal stability	Chemical resistance	Good index range	Stable

1 At 400–800 nm, 3 mm CT

2 Uncoated luminous transmittance: 79% at thickness 6.35 mm; 90.6% at thickness 0.381 mm

3 Per 24 hours

Figure 2. Molded finished optics: Major characteristics of common polymers

Manufacturing process trends

With respect to manufacturing polymer optics, there are two main options: molding, the older of the two options and by far the most common choice for production runs, and single point diamond turning, which has revolutionized the creation of extremely precise optical mold inserts and in many cases, prototype components.

Molding technologies continue to improve

Molding is a two-step process, which first requires creating a reusable mold and then uses plastic injection molding equipment to produce extremely consistent components in high volume at low cost.

- **Industry-wide, the lead times to create molds are becoming shorter**. For example, at Syntec, we have cut our lead times down from 12 or 16 weeks to an average of 6 to 8 weeks, and in some cases as few as 2 to 4 weeks. We build all key elements of an optical mold into a standard base that allows us to interchange a unitized section of the mold. Where applicable, unitized sections are cheaper but have all the robust properties of a full frame traditional mold.
- **Molding machines have become far more sophisticated**, which has substantially reduced the amount of process time (and thus cost) to mold acceptable parts. New machines have closed loop controllers, finite injection control and pressure transducers, data tracking and graphing options that put a lot more science at the fingertips of the process technician, enabling rapid setup and timely corrections.

Single point diamond turning proves its worth

In broad use for optical applications since the mid 1990s (although several companies began use in the 1970s and 80s), a single point diamond turning system, or SPDT, enables skilled manufacturers to produce extremely precise optical mold inserts, eliminating the old grind and polish mold insert methods that are close but not close enough when you are dealing in fractions of a fringe on aspheric forms. SPDT allows for highly accurate surface geometry generation, including toric, aspheres, and diffractives. Equally important, SPDT has allowed creators of optical molds to truly compensate for shrinkage of plastics in all directions, in order to accurately produce and reproduce difficult geometries in ever lower process cycle times. In some instances, you may diamond turn an aspheric form such that when full shrinkage has occurred, the final product is spherical. The same compensation methods can also be used to shorten production molding cycle times through better control of shrinkage.

In short, SPDT can produce finished optics that are highly reliable without requiring a mold, making it only natural to use SPDT to turn plastic materials as prototype lenses. This obviously reduces the lead-time (SPDT samples can be done in as little as a week). It also defers the need for significant capital investment in a mold, allowing for multiple proof-of-concept runs at low cost. (Many times, polymer optics applications languish on designers' laptops because the start up expense of a mold and mold processing, on average $20K, exceeds the R & D budget for the project. SPDT offers the possibility of a proof-of-concept solution completed in under a month for less than $5K.) Moreover, if it will be some time before volume needs ramp up, SPDT is an excellent approach for delivering early production components, deferring mold costs even longer.

Not all materials are suitable for SPDT. Only PMMA, Polystyrene, Polycarbonate and Cyclic Olefins are appropriate, which effectively eliminates a whole range of high refraction, high thermal applications that require PEI (polyetherimide) or PES (polyethersulfone) materials. However, HRDT, or High Refraction Diamond Turning, described in Section 2, is a patent-pending process for achieving repeatable PEI or PES material surfaces that are over seven times smoother than those possible with SPDT alone (between 50 to 60 angstroms versus 400 to 450 angstroms).

			Polymers suitable for both SPDT and HRDT			Polymers suitable for HRDT only	
		Unit	PMMA	Polystyrene	Cyclic Olefin Polymer	Polyetherimide	Polyethersulfone
Trade Name			Plexiglas	Styron	Zeonex	Ultem	Radel
Refractive Index	nf (486.1 nm)		1.497	1.537	1.689	1.604	1.671
	nd (589 nm)		1.491	1.530	1.682	1.590	1.653
	nc (656.3 nm)		1.489	1.527	1.653	1.585	1.641
Abbe Value Vd			57.2	30.8	55.8	18.94	22
Transmission		%[1]	92–95	87–92	90–92	82	80
Max Continuous Service Temp.		°F °C	161 72	180 82	253 123	338 170	356 180
Water Absorption		%[2]	0.3	0.2	<0.01	0.25	0.5
Haze		%	1–2	2–3	1–2		3.9
dN/dT		$x10^{-5}/^{o}C$	–8.5	–12.0	–8.0		
Key Advantages			High transmission & purity Scratch resistance Chemical resistance High Abbe value Low dispersion High melt flow	High index Clarity	Low moisture absorption High transmission & purity Good thermal stability	Impact resistance Thermal & chemical resistance High index	Impact resistance Thermal & chemical resistance High index

1 At 400–800 nm, 3 mm CT
2 Per 24 hours

Figure 3. Diamond-turned finished optics: Major characteristics of suitable polymers

Molding and diamond turning processes combine for optimum flexibility

For production applications where the optics and overall application requirements are well understood, molding is nearly always the right choice. The upfront cost of the mold pales in comparison to the overall low unit cost.

Many applications, however, are breaking new ground. The requirements may be clear, but there are severe system constraints on the optical components. Or the optics demands may be straightforward but the overall level of application innovation requires several iterative prototypes to test usability and ease of integration. Ideally, either SPDT or HRDT, depending on material used, can be used for proof-of-concept, prototypes, and possible beta production needs. This approach shortens the time between development cycles (a major cost savings) and eliminates the need for multiple interim molds and/or sets of tooling.

Some applications are inherently low volume or novel enough that volume may take some time to develop. Eliminating the cost of molds and tooling may be just enough to cost justify their implementation. It is thus clear that the more ways polymer optics manufacturers can solve specific problems, the further it will be possible to push the polymer envelope.

	Proof-of-concept			Quick Prototype			Small Beta Production			Full Volume Production		
	Molded	SPDT	HRDT	Molded	SPDT	HRDT	Molded	SPDT	HRDT	Molded	SPDT	HRDT
PMMA	□	○	■	□	○	■	□	○	■	○	□	■
Cyclic Olefin	□	○	■	□	○	■	□	○	■	○	□	■
Polystyrene	□	○	■	□	○	■	□	○	■	○	□	■
PEI	□	–	●	□	–	●	□	–	●	○	–	■
PES	□	–	●	□	–	●	□	–	●	○	–	■

○ Usually lowest total cost choice (over 95% of the time)
□ Alternative choices, sometimes desirable for unusual geometries or exceptionally tight schedules
● or ■ New flexibility
– Currently not supported
Note: First mold approx. $12K–$25K; each subsequent mold approx. $11K–$20K

Figure 4. Pushing the envelope adds flexibility

HRDT — High Refraction Diamond Turning: A Processing Breakthrough

SPDT is a powerful tool, but used traditionally, its limitations are barriers to "pushing the polymer envelope." SPDT only works with certain "soft" materials, including non-ferrous metals; and PMMA, Polystyrene, Polycarbonate and Cyclic Olefins optical polymers. The limitation to non-ferrous metals is not material since Nickel-plated 420 Stainless Steel provides an excellent solution for mold inserts. However, the inability to diamond turn the high refraction, high index PEI materials, such as Ultem, is another matter. At Syntec, we frequently field requests to create proof-of-concept or prototype solutions using these materials, particularly for telecom, datacom and some defense applications.

Goal

In the 1990s, when telecom was booming and investment money flowed like wine, companies did not seriously object to the need for prototype mold tooling to prove concepts, although they were bothered by the lead-time and helped force the issue of fast turnaround machining of molds. But nevertheless molds it was.

Today there has been a steep sell-off in the telecomm market, putting financial pressure on companies who are simultaneously facing strong competitive challenges. A number of promising opportunities have been scuttled once they reached the proof-of-concept phase simply because of the capital investment required. This market has longed for quick output, diamond turned Ultem prototypes, which are widely held to be impossible, even by GE and IBM researchers, who found that a surface of about 450 angstroms (Å) was the best achievable with SPDT — much too rough for good performance. However, two of us at Syntec, Rick Arndt, VP of Tooling and myself, believed we could treat the current Ultem material and/or adapt the current SPDT process to meet broad industry performance needs of high index, high heat, and transmissive at 1550 nm.

Technical background

Many thermoplastics can be diamond turned to fairly coarse accuracy of within +/- 0.1 mm, for example, sufficient for forming components used in a variety of commercial products. Only a subset of known thermoplastics can be diamond turned to the high levels of precision needed for forming optical surfaces, where RMS surface roughness can be no greater than 100 Å and is preferably much less. Several types of acrylics, for example, have been found to provide acceptable results for optical components using diamond turning, although even these materials can prove difficult to work with except under specific conditions. Many polycarbonate materials prove too soft for diamond turning to desired optical standards.

It is widely recognized in the optical fabrication arts that a plastic material must have suitable surface energy characteristics for precision diamond turning. Among other characteristics, a particular material must have suitable durometer, or hardness, in order to be effectively diamond-turned. Some polycarbonates, as noted above, are simply too soft. Other types of plastic prove too brittle.

Among plastics of growing interest for telecommunications and other applications are those having high transmittivity at red and near infrared (IR) light wavelengths, particularly from about 1200 nm to 1600 nm. Two amorphous thermoplastic resins having this transmittivity property are polyetherimide (PEI), manufactured and marketed by General Electric Company, Pittsfield, MA as Ultem, and polyethersulfone (PES), manufactured and marketed by Solvay Advanced Polymers LLC, Alpharetta, GA as Radel A. Having relatively high indices of refraction (about 1.68 for PEI), high dimensional stability, and good resistance to chemicals and fatigue, both PEI and PES are promising candidates for demanding applications using light in the IR region. Their high thermal properties make PEI and PES particularly advantageous for use in optical fiber couplers in data communications and telecommunications applications. Having high glass transition temperatures and being thermally stable at temperatures in excess of 200°C, these plastics can withstand the high levels of heat required for wave reflow solder processing in printed circuit board fabrication.

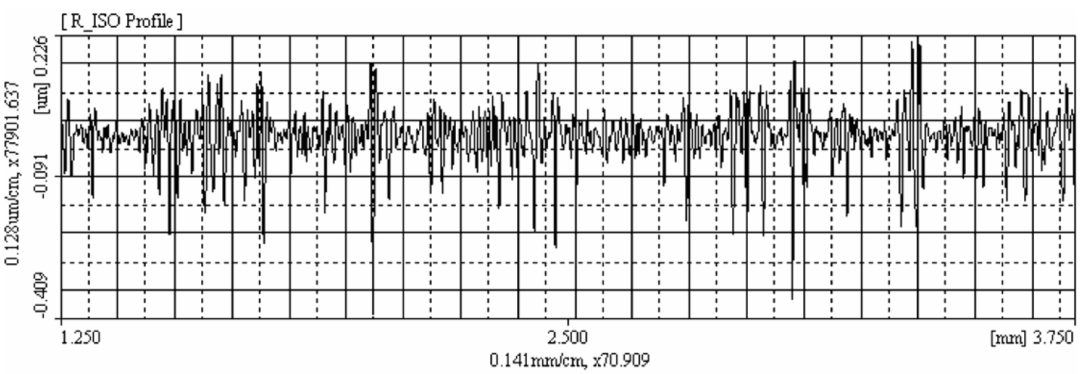
As resins, PEI and PES have been primarily developed and marketed as thermoplastics for injection molding. As noted above, this allows lens elements to be fabricated inexpensively from these materials. According to product literature provided for these resins, precision machining operations, if described at all, are secondary operations at best, that may be employed for specialized use of these materials. As is noted in literature provided by various plastic components fabricators, PEI and PES, without filler materials, are acknowledged to be particularly difficult to machine. The durometer or hardness of stock PEI or PES thermoplastics is very high, not amenable to precision single point diamond turning. For example, a number of plastic component fabricators, in comparing the overall machinability of various plastics, rate PEI and PES as significantly more difficult to machine than other optical plastics; with a rating of at least 7 on a scale from 1 to 10, where 10 indicates the most difficult.

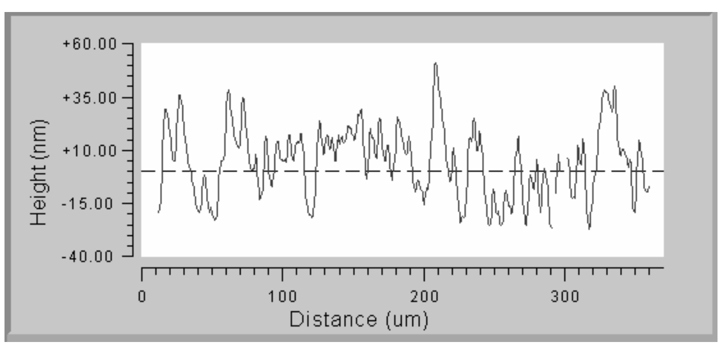
To make versions of these thermoplastics that are more suitable for machining operations, manufacturers mix them with various glass fillers and other materials. However, while these filler materials allow easier machining, they render such thermoplastics as unusable for optical applications. Thus, optical-grade PEI and PES materials, being difficult to machine except to coarse precision, appear to offer little promise as candidates for high-precision optical machining.

For prototyping, as well as for small production runs, it would be highly advantageous to be able to fabricate lens elements from these and similar high index, high thermal property thermoplastic materials using single point diamond turning. However, these materials, as supplied by the manufacturers, are particularly poorly suited to single point diamond turning at the precision needed for optical quality. Conventional procedures for handling and pre-shaping lens blanks from these materials do not yield components with a compatible surface for diamond turning to form an optical surface. Therefore, it is widely held among those skilled in the optical plastic fabrication arts that PEI and PES, and similar types of high index, high thermal property thermoplastics, cannot be satisfactorily diamond turned to the optical quality needed for prototype or production-quality lens elements.

Process

We hypothesized that lens surface failures, which even the best standard SPDT machining produced, were related to a relievable surface energy issue. (Note the surface roughness of the topmost plot file in Figure 5.) If this were true, we further hypothesized that we could relieve the base material and then diamond turn it smoothly. GE recommends annealing any substrates prior to machining, which relieves internal stress and prevents catastrophic material failures, but doesn't resolve the microstructure failures at the surface level. We asked ourselves, what would happen if we developed a custom annealing process that was absolutely repeatable for a given design, based upon material, lens geometry, lens thickness and mass? We further asked, what would happen if in conjunction, we also applied a diamond machining process that takes into consideration diamond shape, rake angle, feed rate, and turning speed?





Top:
Typical SPDT machining; 390 Å achieved; optically unacceptable

Left:
Early HRDT attempt; 163 Å achieved; repeatable but optically unacceptable

Bottom:
HRDT success; 60 Å achieved; fully repeatable and optically acceptable

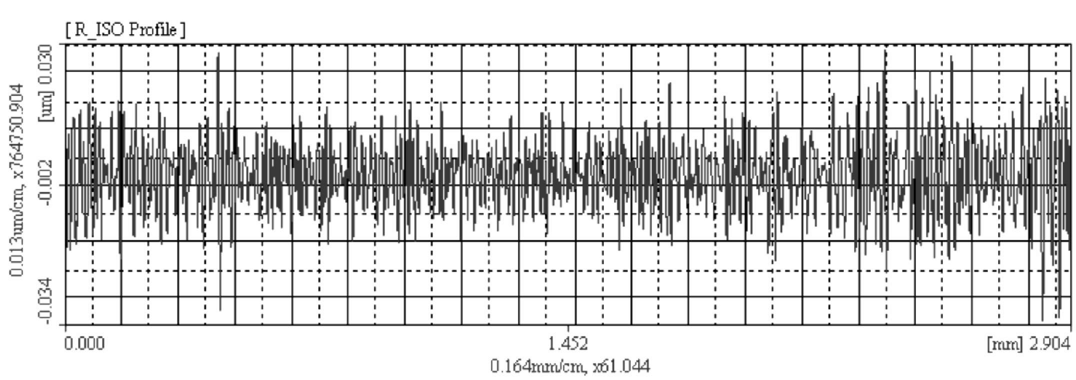


Figure 5. SPDT and HRDT process results

Our very first attempt proved that at an RMS roughness of 163 Å, we were going in the right direction, not optically satisfactory but much better than traditional SPDT. Our next trials broke the 100 Å barrier. After further study of the lens geometry and refinement of the annealing process, we were able to reduce the RMS surface roughness still further, achieving repeatable results of 80 Å, then 60 Å, and finally just below 50 Å RMS. Figure 5 shows plot files of both initial and later tests of HRDT lenses, contrasted with the best possible outcome with traditional SPDT.

Findings

It is critical to understand the desired geometry, and to systematically adjust both the level of annealing and all factors of standard diamond turning process according to that geometry. Once these calculations are complete, you can consistently achieve desired high index, high thermal optical outcomes using HRDT. For example, there are slightly different calculations for using HRDT on each of the lenses shown in Figure 6.

Figure 6. Lenses produced using HRDT

These approaches, which are mandatory for PEI and PES materials, can be customized and applied to other accepted materials for diamond turning. For example, extended annealing of acrylics can relieve the material so there is much less possibility of the birefringence that can occur in some applications if minor surface fractures are present from stress of machining.

The Bottom Line: Where (and How) Does HRDT Pay Off?

This section delves more deeply into situations where HRDT translates into production savings for known applications and, perhaps more important, lowers the cost of discovery in developing innovative applications.

Applications that fit

HRDT opens new opportunities for every application whose optical components can be satisfied with PEI or PES materials, in particular:

- High heat, high index of refraction requirements (i.e., data communications evanescent coupling devices).
- Optics that will be or could be mounted to a PC board prior to the wave reflow process. (This is a huge assembly cost saver in large volume applications.)
- New innovation opportunities where R & D funds are limited or short lead times are needed. (For example, producing five to ten samples using conventional molding will generally require from $12,000 to $25,000 in tooling, depending on complexity, plus up to $2,000 in processing and verification for a total of $14,000 to $27,000. If HRDT is appropriate, the same five to ten samples can be produced for $2,500 to $5,000 depending on complexity, for savings of up to 5X. Also, the mold takes from 4 to 8 weeks to produce, while HRDT finished samples can be completed in about a week, a savings of 3 to 7 weeks. Companies justly place a high value on each week of time saved, sometimes hundreds of thousands of dollars.. Conservatively the value of HRDT in terms of shortening development cycles is at least $10,000 per week, or in this case, $30,000 to $70,000 per cycle.)
- Generally proven design and packaging but inherently low volume, since there are no additional costs for molding and tooling.
- Newer designs and packaging (high or unknown volumes).
- High need for concurrent development approaches with far fewer proof-of-concept and prototype cycle constraints.
- Requirement to leave choices open for final production based on volume and turnaround.

Total cost implications

Of course, total cost for any application depends on numerous variables, well beyond the scope of this paper to discuss. Nevertheless, we can provide a general framework for estimating the likely range of potential savings. This can be valuable in understanding just how to use these expanded polymer material and processing options together best to optimize total costs.

1. Determine whether the optical components are low or high complexity. In general, this will affect the cost of the mold and tooling.
2. Consider whether the entire application is well understood or innovative, that is, breaking new ground in packaging, user interface or functionality.
3. Estimate the likely number of proof-of-concept, prototype, and beta or limited volume production cycles, if any. High optics complexity is likely to increase the number of prototype cycles, while high innovation is likely to increase the proof-of-concept cycles and also require one or more low volume beta production cycles.
4. Optionally, consider a value for every week of development time saved. Generally this savings will equal the number of weeks for creating a mold, less one, times the number of proof-of-concept or prototype cycles where a new or changed mold is required.

Figure 7 below compares sample savings for different scenarios. (Look for a sample Total Cost Calculator to be available on the Syntec website, where you can enter your own values.)

	Low Optics Complexity						High Optics Complexity					
	Known Application			Innovative Application			Known Application			Innovative Application		
	Cycles	HRDT	No HRDT	Cycles	HRDT	No HRDT	Cycles	HRDT	No HRDT	Cycles	HRDT	No HRDT
Proof-of-concept	0	–	–	1	$2,500	$14,000	0	–	–	2	$10,000	$49,000
Prototyping Cycles	1	$2,500	$14,000	1	$2,500	$12,800	2	$10,000	$49,000	2	$10,000	$44,000
Beta Production Cycle	0	–	–	1	$2,500	$12,800	0	–	–	1	$5,000	$23,000
Volume Production[1] Cycle	1	$15,000	$3,000	1	$15,000	$3,000	1	$30,000	$3,000	1	$30,000	$3,000
Total Cost		**$17,500**	**$17,000**		**$22,500**	**$42,600**		**$40,000**	**$52,000**		**$55,000**	**$119,000**
HRDT Advantages												
Hard costs		-$500			$20,100			$12,000			$64,000	
Development Time Savings		$30,000			$90,000			$120,000			$270,000	
HRDT Total Advantages		$29,500			$110,100			$132,000			$334,000	

Assumptions	Low Optics Complexity	High Optics Complexity
Cost of first mold	$12,000	$25,000
Savings for subsequent molds (both in time and $$)	10%	20%
Cycle time to make mold (in weeks)[2]	4	8
HRDT weeks saved per cycle	3	7
Development savings per week	$10,000	$10,000
Beta Production Quantity	0	10
Volume Production Quantity[3]	1,000	1,000

1 Example assumes volume production is always molded
2 Molds vary considerably in complexity, time needed to make them also varies, 4–12 weeks or even longer
3 Break even point is often achieved at production volume of 100, example assumes 1000

Figure 7. Total cost comparison

Summary

Given the major drivers of lowering cost and removing space and weight limitations, new materials and new processes would clearly open even more markets for polymers — markets that do not exist now as well as markets that would clearly grow "if only…."

Some soluble barriers and markets are clearly identified

If there were polymer optics materials suitable for higher ranges of IR applications, many security and defense-related solutions become economically feasible.

For example, army field operations personnel carry up to 120 lbs of supplies and equipment, very tiring since the average foot soldier is 170 lbs. These include the hand-carried imaging units that provide visibility to the unmanned surveillance and detonation vehicles in high action regions, both airborne (UAV) and ground (UGV). These imaging units commonly utilize FLIR (forward looking IR) or general Infrared systems that operate in the 3–5 micron and 8–12 micron range, giving them ample access in either high or no light conditions, even sand storms or blizzards. Currently no polymers transmit significantly (greater than 70%) past 2.2 microns; in fact, none today transmit past 38%. As a result, the materials used for these tasks are inherently costly (about forty dollars per gram), heavy (5.3 g/cm^3) and subject to expensive optical techniques of grinding and polishing.

If such material existed, a plastic solution would cost on the order of thirteen cents per gram, be capable of moldable openings for a wide array of possible aerodynamic or protection lens configurations, and most importantly, be light weight (1.1 g/cm^3, a fifth of the current weight). This is a huge savings for the field personnel that can translate into longer flying or driving range or more fuel, ammunition or other troop supplies. Moreover, if you extend the range of materials that can be processed without a mold, many experimental or low-volume applications become practical.

Other barriers to be tackled include:

- More thermally stable materials. Currently the index of refractions shifts significantly with temperature (dN/dT) in plastics. Stabilizing the index over broader ranges is critical for further acceptance of polymer options.
- Higher temperature materials for the visible range.
- Harder surface resistances for better scratch avoidance.

Some barriers are not technical, but rather awareness and collaboration

Sometimes, the barriers are not technical. For example, while popular culture may equate DNA ID and/or unmanned air and ground vehicles with super expensive "Star Wars" solutions, many opportunities exist for using these technologies to improve everyday life. Unmanned airborne vehicles for the forestry service or law enforcement, news or traffic reporting; better security systems for the home or for baby monitoring; high heat high index materials for DNA identifications for medical applications are all possible today. Similarly the time may well be here for most cars to have night vision systems. Plastic optics can pave the way to make all of these a cost effective consumer reality.

While it will take serious collaboration between and among optics companies and the organizations developing products to address economic issues, it is in the long-term best interest of all of us to work together. Often one organization or another is rightly concerned with the importance of protecting valuable knowledge assets. However, there are many reasons to work to maintain a balance. To quote John Seely Brown, author of the bestselling The Only Sustainable Edge: Why Business Strategy Depends on Productive Friction and Dynamic Specialization, "When an organization goes out of its way to make sure that no idea ever leaks out, the consequence is that no idea ever leaks in either."

Design is front and center

The main premise of this paper is that the major keys to continued polymer optics expansion are the specific characteristics of available materials and the sophistication of manufacturing processes in implementing designs. With respect to desirable polymer characteristics, some may require a new class of polymer from materials manufacturers, but many more are being achieved by introducing new grades of materials, optimized appropriately in much the same way as glass. With respect to the sophistication of manufacturing processes, the level increases steadily as optics manufacturers find innovative ways to use molding or machining as costs, volumes and applications dictate.

The major drivers continue to be the relentless need to integrate into more and more applications with smaller, higher performing components, in lighter packaging, at lower cost and superior reliability. Note the critical role of design. At Syntec, we take the perspective that product design, tooling and molding design, and total manufacturability design of the completed assembly are not individual static specifications but dynamic, interrelated parts of a total solution. Fundamentally, we believe this approach of systematically building upon everyone's capabilities is the best way to push any envelope, including the polymer optics envelope.

This paper was originally presented by author, Paul R. Tolley, at the SPIE 2005 Optics & Photonics conference in San Diego, and subsequently published in the Conference Proceedings.

Paul Tolley is Vice President and General Manager of Syntec Technologies, Inc., and co-developer of patent pending HRDT (High Refraction Diamond Turning) process.