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Tolerancing for economies in mass production of optics

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Abstract

With the development of new, high precision optics production machinery there is a need to re-examine tolerancing of cosmetic standards, physical dimensions and optical performance. This paper will deal with some of the tolerancing trade-offs developed at Plummer Precision Optics, which have proven successful in reducing manufacturing costs without adversely affecting optical performance.

Although the observations and suggestions set forth herein were promulgated, primarily, for the persons who must purchase or fabricate production quantities of optical systems, most of them apply, to a lesser degree, when only limited quantities are involved.

At the outset, it should be pointed out that the data given is based on techniques and production equipment employed in the Plummer Precision Optics facilities, and may not necessarily apply in other fabrication plants where widely differing equipment and techniques are utilized.

Virtually all the optical systems design work of the last two decades has been performed on electronic computing equipment, and they are marvelous machines on which to design as well as tolerance the individual optics and surrounding metal components. However, without the guiding hand of an experienced optical design engineer, the computer sometimes give us designs and tolerances which approach perfection in optical performance, but because the optics are to be used in a price sensitive instrument, the system is completely impractical from an optics fabrication standpoint. The author will attempt to cover several areas in the fabrication cycle where the design constraints and optical tolerancing can have a profound effect on the cost of manufacture.

The glass types selected by the designer can affect costs in several ways. 1. One should, to whatever extent possible, select glass types which are regularly produced in large quantities. This usually means that the glass is immediately available and at a reasonable price. Raw glass from U.S. sources range in price from $3.00 to $300.00 per pound in 1000 pound lots. The less frequently used glasses are, for the most part, produced in small platinum crucibles at an understandably high cost and oftentimes there is insufficient inventory on hand from which to produce a goodly quantity of pressings. 2. The stain characteristics of the glasses also become an important cost factor, in that, when utilizing highly stainable glasses, extreme care must be given during the fabrication cycle to protect the polished surface prior to the anti-reflection coating. Although the stains have little effect on optical performance, they do pose cosmetic problems. 3. Some glass types, primarily those containing rare earth ingredients, are unusually soft and test the skill of the optician during high speed grinding and polishing. Even after the optician has produced the desired surface, the optics are quite susceptible to scratching during subsequent operations of cleaning, inspection, centering, coating, and cementing.

High ratios of thickness to diameter should, if possible, be avoided. We normally consider a lens which has a diameter no greater than 9 times its minimum thickness to be easily manufacturable to a figure tolerance of 1/4 wave over a 50mm diameter. One can, with special blocking and careful polishing techniques, obtain reasonably good figure tolerances on lenses having diameter to thickness ratios up to 20 to 1. Above 20 to 1 ratios, the cost of manufacture rises dramatically.

Designers who are not conversant with the latest and most sophisticated centering equipment will often spell out unduly loose tolerancing on diameters of lenses and to counterbalance this will call for extreme accuracies for eccentricity. The designer may also attempt to avoid glass to glass edge contact in assembly, because he is fearful of the fabricator's ability to establish bevels which are truly concentric with the optical axis of the lens. The centering equipment utilized in the Pennsburg, Penna. plant is routinely capable of maintaining, on a typical 50mm diameter lens, diameter tolerances of ±0.025mm and bevels concentric to the optical axis within 30 to 60 seconds depending on lens configuration. By using these tighter lens tolerances one can make or purchase metal parts with correspondingly looser tolerances and at lower cost. By using glass to glass edge contact in assembly, the need for accurate and sometimes intricate metal spacer rings can be eliminated. The rationale, here, is to specify closer tolerances on the optics, where, because of the centering equipment utilized, it costs no more, giving latitude in tolerancing mating parts to make the system more cost effective.

Designers should also, where possible, avoid lens with radii so short that fabrication can run only one lens per block. Generally it is far more difficult to hold good figure tolerances on single lens than on blocks containing 3 or, even better, 6 lenses. It should also be noted, when using high speed grinding and polishing techniques, that the time cycle on a block of 6 lenses is but slightly higher than a single lens. Where it is possible, it is often less expensive to utilize higher index glasses (usually more expensive) in order to avoid sharp radii which necessitate single surface fabrication.

Beauty defects such as scratches, pits and bubbles within the glass is another item which, besides affecting the cost of manufacture, is often the source of much wrangling between the fabricating department and final assembly. Modern machinery, and good tooling and techniques make it relatively easy to meet 80-50 and 60-40 cosmetic standards of Mil-C-13830A. However designers and engineers, to be absolutely on the safe side, will sometimes specify cosmetic standards far above the functional needs of the optical system, and in so doing, add nothing to the performance, but due to increased rejection rates, increase the final cost of the instrument. A good rule of thumb to remember is that "optics are made to look through, not at."

Tolerances applied to center thicknesses of lens can substantially affect the cost of manufacture. Center thickness tolerances of less than ±0.05mm become difficult to hold in mass production whereas, with good tooling and machinery, one can economically maintain tolerances of ±0.1mm. The further loosening of tolerances to ±0.15mm and above, will result in only minimal cost reduction.

With modern centering and edging equipment, the cost of grinding accurate bevels on one or both sides of a lens is negligible and, in fact, in some cases may actually reduce cost of production, in that beveled lenses are far less likely to be chipped in the subsequent manufacturing operations, and in final inspection and assembly.

In those systems which demand close tolerances on focal length, the person who is tolerancing the optics will often specify a change in radius to match the index of refraction as actually measured on each batch of pressings. The cost of sophisticated tooling to mass produce a system makes this approach quite impractical and in such cases we are usually able, by paying a surcharge of 2.5% to 20%, to purchase pressings to close index tolerances, which eliminates the need to change radii on tools to insure close focal length tolerances.

In those applications where additional light transmission is desirable, one can specify multi-layer, anti reflection coatings rather than the more commonly used magnesium fluoride single layer. In a typical optical instrument having 10 air to glass surfaces the transmission would approximate 60% for uncoated optics, 85% for magnesium fluoride single layer coated, and 93% for 3 to 4 layer high efficiency coated. These percentages can vary considerably depending on the index of refraction, however the above assumes a typical mix of indices from 1.52 to 1.70. The application of multi-layer coatings entails the use of expensive vacuum systems and generally demands the monitoring by sophisticated and highly trained personnel. These two factors, plus a longer cycle time adds substantially to the cost differential between single and multi-layer coatings. The industry trend away from magnesium fluoride toward multi-layer coatings will, I am sure, necessitate the development of better equipment, monitoring devices and techniques, which, in turn, will result in a substantial reduction in cost of production.

Last, but far from least, in considering the cost of production of optics, is the attitude of the inspector, who must make the decision on the acceptability of the optic, subassembly, or the final instrument. In our 35 years experience in optics fabrication, we have encountered, in our own organization, as well as our customers, the entire gamut of quality control personnel attitudes. Unfortunately, but happily infrequently, we run into those inspectors who feel they have not earned their salary unless they find a certain percentage of rejects, regardless of the level of quality of those items submitted to them for inspection. One should strive to instill in their quality control personnel the positive attitude of diligently looking for functionally good pieces which are cosmetically acceptable. An inspector serves his company well when he comes to the realization that, for most optical instruments, fidelity of resolution is infinitely more important than minor cosmetic defects which will not detract from its proper function.

The following demonstrates the average cost effect under various tolerances on typical lenses 25 to 50 millimeters in diameter. The figure 100 represents the base cost and the subsequent figures indicate the increasing cost due to tighter tolerances or design constraints.

Diameter tolerance)	±0.1	±0.05	±0.025	±0.0125	±0.0075
in millimeters)	100	100	103	115	150

Center thickness)	±0.2	±0.1	±0.05	±0.025	±0.0125
tolerance in m.m.)	100	105	115	150	300

Stain characteristic)	0	1	2	3	4	5	5+
of the glass)	100	100	103	110	150	250	500

Number of lenses)	25	18	11	6	3	1
per block)	100	105	115	130	175	300

Eccentricity tolerance)	6 min.	3 min.	2 min.	1 min.	30 sec.	15 sec.
in light deviation)	100	103	108	115	140	200

Figure tolerance in)	10-5	5-2	3-1	2-1/2	2-1/4	1-1/8
λ(Power & irregularity)	100	105	120	140	175	300

Diameter to thickness)	9-1	15-1	20-1	30-1	40-1	50-1
Ratio(assume figure of 3-1)	100	120	150	200	300	500

Beauty defects)	80-50	60-40	40-30	20-10	10-5
per Mil-C-13830A)	100	110	125	175	350

Raw glass cost)	$3.00	$5.00	$8.00	$15.00	$25.00	$50.00	$100.00
in 1000 lb. lots)	100	108	115	125	135	200	350

Coating specifi-)	Uncoated	Mag. Fl. Coating	3-4 layer multi coats	< 4 layer multi coats
cations)	100	115	150	200 - 500