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Review Article

Injection molding of optics for high volume consumer products

Rien de Schipper

Penta HT Optics, Glaslaan 2, Building SWA532, Eindhoven 5616LW, Netherlands

e-mail: r.de.schipper@penta-ht-optics.com

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Abstract

For high volume consumer products using optical technology, plastics injection molding is a very suitable technology. In optical component fabrication, astonishing results are be booked. However, to achieve success, excellent performance is needed in mastering different technologies such as polymer processing, evaporated coatings, tool making, ultra-precision turning of metals and optical metrology.

Keywords: consumer optics; high volume manufacturing; injection molding; polymer optics.

1. Introduction

Our daily life is filled with mass manufactured items, almost all of which injection molded plastics form a part. Many consumer products and also some really popular ones such as CD/DVD players, gaming devices and mobile phones use plastic molded optical parts. Choice for the molding process has some obvious reasons: it is a fast, one step, cyclic process, with a well developed supply base for machines and tools and most important: cheap raw materials. In many ways, these general characteristics also count for the specialty of optical molding. If in the 1990s the laser spurred the use of plastic optics, and a decade ago the CMOS-image sensor, now the LED and photovoltaics will bring a new wave of growth to the sector. Although the three categories of optics are very different in characteristics, they are all governed by the same rules for mass produced products.

Optical molding as a technology has been developed over the past 30 years. A major step in the development has been the advancements in the tool making technology, to be more specific the ultra high precision turning of optical mold surfaces. Another factor, contributing to the success is the application of dedicated metrology equipment. Over the years and many companies found out that successful optical molding is in fact a chain of successful executed operations, all to be mastered on a state-of-the-art level [1].

2. Characteristics of consumer optics

With the 7 billionth world citizen born in 2011 and all of them consumers in some form or way, consumer products' characteristics are driven by the large volume needed. For durable goods, this can lead to volume markets of 1.5 billion units per year like in the case of the mobile phone. A number that is even topped by volumes for consumables, such as lamps. However, in general one can say that with 5 M pieces per year all characteristics of high volume will surface. This high volume feature is a sort of club with which all other characteristics of the product are chastised and can be brought under control. The mechanism behind it is simple. The high volume is a divider for the initial cost, so upfront investments become virtually insignificant in the end. At the same time it is a multiplier for profit: even a few cents profit per part gives a nice operating result at the end of the year.

The upfront investment starts with the product R&D, where basic manufacturing process choices are made. The drive towards low cost forces the designer of the product toward the optimal price/performance, where he can use all design potential, and even up to requesting new material developments or technology breakthroughs. CD/DVD is such an example for which new optical materials were designed (such as optical polycarbonate grades) and for which a new generation of molding tools saw the light. Thus, in the end the consumer optical part will be highly specialized and optimized for the purpose for which it has been designed. Several design and engineering loops and prototype trials will be performed before definitive choices are made.

Other initial cost will be the building of manufacturing floor space, adapted for the specific requirements for the products, such as clean rooms. Injection molding machines and post-processing equipment such as automated degating and optical coating equipment can also form part of the initial investment for high volume products. Last, but not least in terms of capital investment, is the need for dedicated metrology equipment, such as phase-step interferometers for laser optics and automated MTF evaluation machines for imaging optics. Free form surface optics is a new challenge in this respect, where industry is still struggling to find a fast and affordable method for product qualification in a manufacturing environment.

The need for high initial capital investments makes R&D for consumer optical applications the domain of large companies. Examples are Sony/Philips for CD and Nokia for cell phone camera lens. They in their turn will recruit or even ground specialist companies to fill in the created demand. Staying with the given examples we can name here: Konica-Minolta, Kodak, Largan, and Heptagon. These specialized companies can make good business at the start of the life cycle of the product. However, owing to the high volume attractiveness, many companies will show interest to grab a share of the market and try their luck. Of which some will disappear quite soon, but others survive. In short, this is a highly competitive environment under continuous change.

All of this leads to a life cycle of such an optical part, which starts at a high price, produced by well-known companies. Then year after year, a price reduction is recorded, up to 20% per year, basically as long as the product lives. An example is the lens with VGA resolution for cell phone and other consumer products. In Figure 1, the yearly price reduction curve of 20% is compared with the actual market price of the lens. Although the graph in Figure 1 stops at 20 cent per lens, this has been proved not to be the real end, which will be in the range of around 10¢.

To make this price reduction possible many factors contributed such as size reduction, specification relaxation, higher degree of automation, better and more optimized tools, higher production yields due to experience and of course lower profit margins, due to an increase in the number of vendors.

Unfortunately, even when fulfilling the need for the yearly cost reduction, a company can never be sure of its business. Technology competition also needs to be taken into account in the case of high volume products: stakes are simply too high to ignore that. Taking again the example of the VGA lens, already two technology shifts occurred, from glass elements to full plastic at the start, and around 2008 the shift towards wafer level optics, based on glass/plastic hybrid technology.

3. Low cost for mass manufacturing

From the above description of the characteristics of high volume optics production it is clear that it is not so easy for a company to earn money with this business, but when you have the right strategy and a flawless execution, the reward is big. In short, the strategy can be formulated as to make timely choices to reach the optimal cost/performance the market is asking for at that point. Bear in mind that required performance can be a flying target, influenced by choices at the application level. In addition, one cannot overstress the importance of the right timing: when running a high volume production, being too late with introducing a cost saving technology can be very expensive indeed.

To find out which choices are to be made to reach a low cost at all times, it is very useful to do an analysis of the cost models for injection molded parts. These models are widely available in the market and many companies have their own with company specific features. Of course it must be taken into account that some adaptations to general models might be needed to make them fit for the specifics of optical molding.

In Makinen [2], shows an analysis and determines which parameters in the calculation have the largest influence on the cost of the molded part (Figure 2). These prove to be yield, cycle time of the molding, machine uptime and number of cavities. Surprisingly as it may seem, materials price is not in the list, although through these four, the material choice will be one of the major factors, as we will see.

Further analysis of the cost contributing factors illustrates the fact that the design of the part is the determining factor (after the volume). Even to such extent that an excellent part design can make the actual manufacturing seem a trivial matter. This will become clear when the yield factor is analyzed in depth.

4. Yield

Yield can be defined as the % of manufactured parts which is fit for use at the customer's site. Because it is not practical to learn the yield so late in the manufacturing process, the aim is to have a qualification method which for 100% covers the customers' requirements already at the instance of manufacturing the part. Discussions will take place between companies on how to qualify the parts and there is a natural tendency to stay on the safe side from the customer's point of view, in other words over-specifying of the part. This is a first, most of the time, not detected source of yield loss. Parts are trashed, because of failing for a too stringent test.

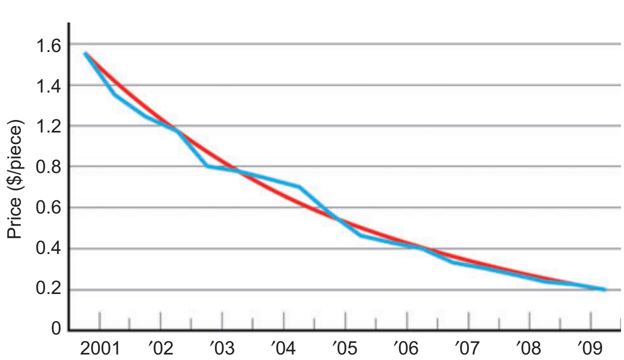

Figure 1 Market price of a VGA lens function for mobile phone in $/piece, compared with 20% annual price reduction.

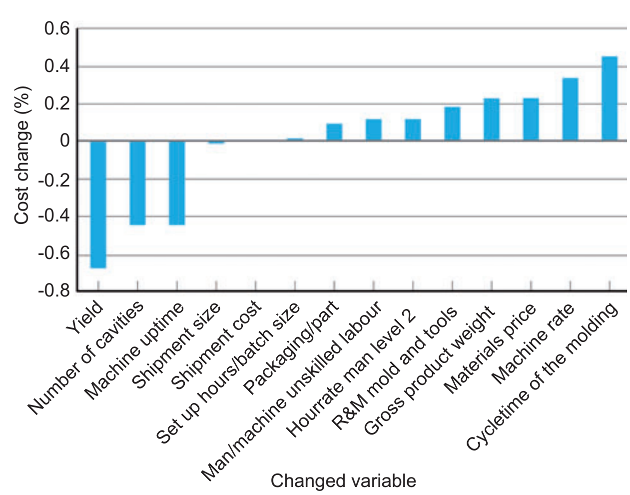

Figure 2 Influence of parameters to the total of the manufacturing cost [2].

In standard plastics molding processes, the yield is often near to 100%, but this is not the case with optical parts for high volume consumer parts. The drive to optimal cost/performance leads to design choices that make things more critical, e.g., a fixed assembly is cheaper to do, but requires an accurate focal length of the manufactured lens. Optical requirements that can drastically reduce the yield are: visual aspects (scratch/dig), surface irregularities, lens element center thickness and run out in alignment of optical surfaces. Best remedy here is to keep an open dialog with the customer on the requirements: with no dialog yield issues may be impossible to solve and chance for success becomes small. When requirements are clear and undisputed, the right choice of tooling is the next hurdle to take. Tools should be stable in terms of back-to-front alignment at all times, even after 500 000 shots, which is the usual life expectancy for a mass production tool. Optical surfaces of tool inserts must be at least as good as the requirements for the part itself, which is an identical copy of the tool surfaces with respect to surface finish. One of the most difficult things to determine is how and how much the curvature of the surface in the tool must be corrected, to just achieve the right curvature in the product after the product has cooled down and all shrinkage has taken place. This definitely belongs to the 'know how' of a company and gives a distinct competitive advantage when mastered to the right level.

Then, as a third leg under the stable yield platform, having sound agreements with the customer and in possession of excellent tooling: use of statistical process control (SPC). Choice of the right product quality parameters (indicative for the fit for use at the customer end), not too many and easy and reliable to check is the cornerstone of SPC. This leads to a relative cheap inspection method of three consecutive shots to be measured every hour or even 2 h. Lens thickness measurements, spot measurement, and interferometry can perform such monitoring tasks, provided that the production equipment is under close loop control and guarded for being within predetermined tolerances for the most important settings on the machine (such as injection temperature and pressure). Cpk values of >1.66 must be reached, but often we see that Cpk values of >2 are realized. This is a good indication for very low ppm figures.

5. Cycle time

Injection molding is a short cyclic process. The cycle starts with injection of the molten plastic in the closed mold, followed by a cooling phase in which the material solidifies after which the mold can open, the part is removed and the mold closes again. The production cycle of a DVD disk is around 3 s, where all parts of the cycle have an (approximately) equal contribution. This is mainly because the disk is thin: only 0.6 mm. When the thickness of a molded part increases, the time needed for cooling is growing exponentially. In Figure 3, graphs are shown, which relate the thickness to the cooling time of the part. These graphs clearly show that it is rewarding to strive for a minimum part thickness to reduce cost. The two lines in the graph represent two commonly used materials, acrylate (PMMA) and polycarbonate (PC). For thick parts the difference in cooling time is dramatic.

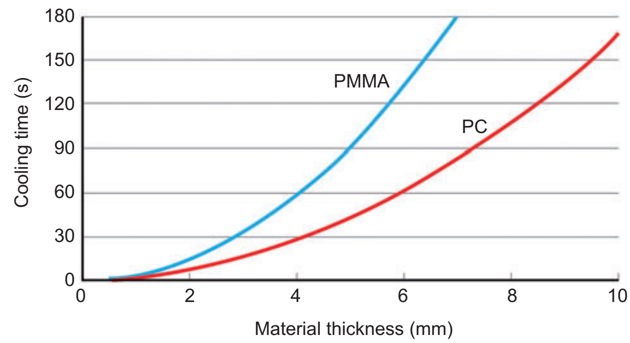

Figure 3 Influence of material choice and thickness on the cooling time [3].

Another influence on the cycle time is the needed accuracy of the optical part. During the cooling the part shrinks and the shape of the surfaces is not an exact copy of the mold anymore. The amount of shrinkage is directly related to the process conditions: the more extreme molding conditions are (high pressure and high temperature), the longer the cycle time. In particular, a high mold temperature is of strong positive influence to the shape accuracy of the lens, but causes the cooling time to go infinity when it comes near the glass transition temperature of the plastic of choice.

A subject related to cycle time is the use of a hot runner. This is a system built in the mold that reduces the waste of material in production, by preventing the cooling down of the cavity feeder system. For optical molding, experience has shown that the advantage that the system has in terms of material cost savings are mostly undone (or worse) because of cycle time increase. The reason is that mold temperature settings need to go up to anneal stresses caused by the material inhomogeneities, which occur in the hot runner system. Only with very small components a hot runner system pays off.

6. Machine uptime

The uptime is defined as the time in which all necessary available equipment and personnel are able to produce parts. High volume production will run 24 h/day and 7 days/week. One influencing factor here is the quality of machinery and tools (mean time between failure). In the case of modern equipment from renowned suppliers and a rigidly executed (daily-weekly-monthly) preventive maintenance schedule, this is not an important factor. More important is production start-up time. A well-designed production process only needs a few minutes to run in, but in the case of a more critical product and combined processes (such as in-line assembly), start-up time can be much higher. Most important, however, are demand variations. Take a consumer product running at a rate of approximately 1–2 million/month. For a manufacturing plant running machines with an output of 125 000 products per week it means that they have to be able to switch on/off from two to four machines.

When the demand variation requires a short reaction time to cope with the volume difference, it means that on average 25% of the equipment will be idle. For a manufacturing unit it is not likely to find other load, exactly fitting a temporarily low level demand, because of the special characteristics of most optical parts. Of course it helps when you have a big manufacturing unit, but only then if not all customers have the same seasonal effect. This cost of demand fluctuation is often not taken into account in the product cost calculation, or treated in a far too optimistic way in terms of finding an easy solution. This leads to unavoidable operational losses.

7. Number of cavities

With plastics injection molding there is the choice to make how many cavities a mold must have. The number of cavities determines the number of parts, which are produced in one cycle. Thus, the natural tendency is to determine the number of cavities by choosing the optimum between increase of initial cost (mold cost) and decrease of part manufacturing cost. This theoretical approach is much too simple unfortunately and has caused much trouble in production start-ups and loss of investment, due to necessary rebuilding of tooling. The problem is that the increase of number of cavities influences the most important parameters in a negative way, because of a more narrow process window. More cavities will cause:

- higher start-up time,
- lower yield,
- lower life time of the tool,
- higher cycle time,
- more than linear increase of tool cost, due to required accuracy,
- more difficulty to cope with demand fluctuations.

The problem here is to estimate beforehand the magnitude of the influences. The best approach is to build experience with a class of products by starting with a single or a dual cavity. When still in the prototype phase, this is a very realistic proposition. When experience is gained, the choice can be made for a 4, 8, or 12 cavity tool. Going to 16 cavities and beyond is only safe when a lower cavity number tool is running perfectly with a yield of near 100% and an acceptably wide process window. This type of tool is only used for long living products or product generations.

8. Cost of a plastic part

It is an interesting exercise to put all of the above knowledge in an available cost model and see where it ends up. This has been done in Figure 4 for the mainstream of optical parts for consumer products: lenses with a size up to 20 mm and thickness up to 3 mm. Part cost has been calculated in function of the yearly volume and with realistic variation in materials, specifications, and all optics uncoated/untreated.

For the real low volume breaks (1 and 10 pcs), a possibility of ultra-precision diamond turning has been assumed. However, this might not always be possible, because for the diamond turning process, material choice is even more restricted as for injection molding: PMMA being the primary material of choice and with some limitations cyclo-olefinic-(Co)polymer (COC/COP). For the higher volume breaks, cost per part reaches down to 10€ cents and below. Whether one ends up with the price in the upper half of the tolerance band or in the lower half depends on the boundary conditions of the product and the manufacturing environment. Influencing factors are: set-up of the manufacturing (e.g., clean room, country, cost of overhead) and product characteristics (required precision). It is remarkable to see that the volume is so much more important to attain a low cost as compared to the required accuracy.

9. Accuracy

Thus, the question can be raised: what precision can be bought for 10 cents? In many publications, such as [3], a list of such publications is given and tables can be found of attainable tolerances. In some, the header of the column on the right is low cost quality, making the connection between low accuracy and low cost. From Figure 4, one can see that this term is slightly misleading: real low cost comes with the volume and only to a lesser extent with the quality level. Some product parameters do not have a strong relation to the cost of the part. For instance, a number of optical characteristics, such as tilt and de-center in the lens and surface finish are mold-bound. For high volume products, tools are demanded with long life expectancy and this means baseline quality is needed of used materials and tool manufacturing processes. Some of these processes, such as the ultra high precision turning of nickel plated steel inserts, deliver a standard minimum quality. They cannot go below a minimum performance (to save cost) and have upper limitations, natural to the process, where more available money does not change the situation. Figure 5 gives a table showing what tolerances can be achieved for some main lens parameters. The values can be used in tolerance/performance simulations, such as the Monte Carlo analysis. The right hand column links to the lower limit of the graph in Figure 4 and the left hand column to the upper limit. One

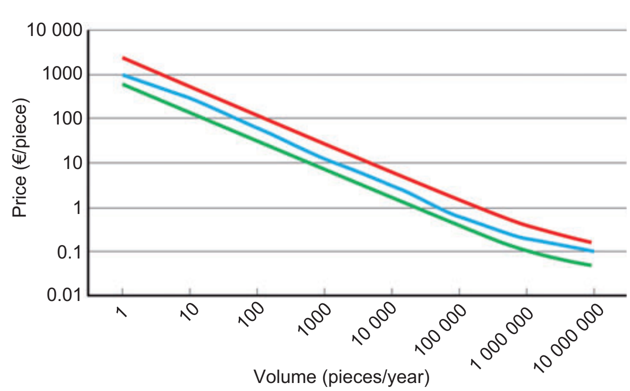

Figure 4 Price of plastic optics as a function of the yearly demand.

Lens attribute	Normal tolerance	Tight tolerance
Surface radius	±2%	±0.5%
Focal length	±3%	±1%
Power (Fringes)	5-2	1
Irregularity (Fr/10 mm)	2-1	1
Center thickness	±0.03 mm	±0.01 mm
Mechanical diameter	±0.03 mm	±0.02 mm
Decentration surface 1 to surface 2	0.030 mm	0.007 mm
Decentration optical – mechanical	0.030 mm	0.010 mm
Surface roughness Ra	15 nm	5 nm
Bubbles and inclusions	1×0.16	1×0.10
Scratches	2×0.10	2×0.06

Figure 5 Typical tolerances in optical injection molding.

could argue that even wider tolerances will make the cost go lower. This is definitely true, but at some point the part becomes a standard plastic part and not an optical component. For such parts, the standard cost models for plastic moldings would apply better.

A boundary condition for achieving the tolerances stated in Figure 5 is the quality of the mechanical aspects in the design. Here the rules for designing a plastic part should be followed with great care. Special attention is needed for the gate design, usually a lot larger than standard. Also, draft angles should be chosen generously, with values of degrees, rather than tenths of degrees. They will help to reduce the forces of ejection and prevent deformation of the optical surface. One rule of designing a plastic part – use even wall thickness all over – cannot be abided in many cases. The optical design will require a certain curvature and in the case of a biconvex lens or a biconcave lens, thickness variation is a given. But even in this case, good designs can alleviate the problem. With biconcave lens a minimum center thickness is needed. For a biconvex lens a minimum edge thickness must be observed. It is always advisable to design mechanical features around the optical surface to protect it against handling scratches.

When discussing accuracy of injection molded optics, special attention is needed for characteristics related to the polymer material. Three of them need to be mentioned here, as they can be a show stopper for the use of plastics in an optical application. First, we have the limited choice in available combinations of index of refraction and Abbe value, illustrated in Figure 6.

Owing to this limited choice, a design may have fewer possibilities to be optimized. A second material characteristic becomes important when the optical system function relies on the use of polarized light. Some optical plastics such as polystyrene and polycarbonate have a high intrinsic birefringence combined with a large photoelastic coefficient. These materials will cause different orientations of polarization of the light beam to see a different index, and thus causing aberrations [3]. A third possible hurdle on the road to application of plastic is the temperature behavior of the material. We have the maximum use temperature of course, which is in general between 120°C and 160°C. Less obvious, but rather devastating in some applications, is the change of index of refraction with the temperature. For all optical polymers this value is approximately -0.0001/°C. Thus, for a use temperature range of 100°C, a change in index of -0.01 occurs. This means that for those applications where such a wide range can be expected, such as in an automotive environment, the use potential of plastic optics can be seriously limited, even though the volume might be large enough to set all other signals to green. Optical systems that have an in-built autofocus, such as DVD and BluRay and mobile phone cameras, suffer less from the consequences of this effect, which largely disappear with refocusing.

During the past decades numerous avenues have been taken toward solving the maximum use temperature problem and develop an optical plastic stable to 300°C. The benefit would be that a plastic optical component could be subjected to post-processing at elevated temperatures and survive. Although some steps have been made, for the mainstream materials, the progress has taken us not further than 140–180°C, which is good for curing glue, but not high enough for lead-free reflow soldering. Solving the second problem (index change) is even more difficult to solve because of the laws of physics involved.

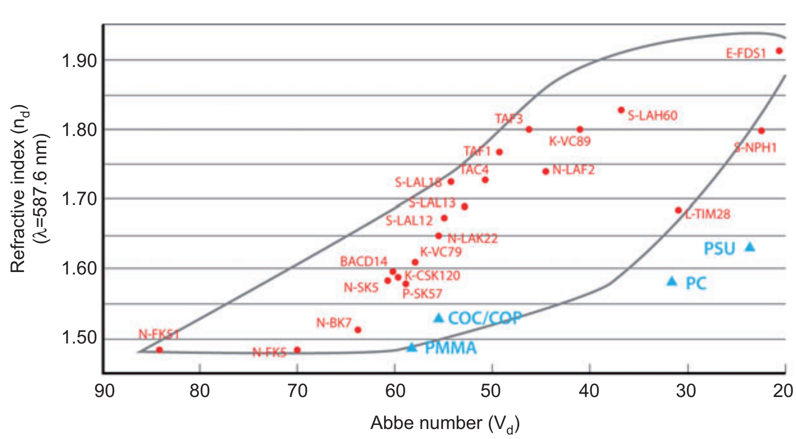

Figure 6 Choice of polymer materials compared to glass molding materials.

10. Observations about high volume manufacturing of optical parts

When all of this is put to practice in real life, results can be dramatically different between companies, but also for one company over time. Let us suppose we have a good design to begin with, which will put us in a good starting position. A good design can be defined here as just fit for use in the end application, abiding the requirements of mass manufacturing, such as allowing for the tolerances as stated in Figure 5 and other rules for sound design of plastic optical parts. The observations listed in the following section are not so much about the technical aspects of optical components but more about the managerial aspects of mass production of such goods.

10.1. Observation 1: when high becomes large

Growing in manufacturing volume together with a successful customer is almost ideal: good understanding of what is needed and stable relationship. But beware of this customer becoming too large, which easily can occur when the application under hand is a mass consumer product. If you let it happen, the life of the company can become tied up in the success of only one customer. A second aspect is life cycle management. Consumer products can have a nice long life as a generic product: 20–30 years easily. But within this life drastic changes can occur, examples being the speed race in CD-ROM and just recently the Megapixel race in CMOS cameras. Often this race requires technology steps of certain components. In addition, count on it that the optical components are likely to be the victim at some point in time, because most of the time the optical components are critical for the total functionality.

10.2. Observation 2: price pressure

The huge price pressure is of course not limited to the optical components only but also applies to the total supply chain, from the basic materials to the customers' hands. It is important to have a good eye on possible changes down the chain, which can influence the life of the product in a factory. This can be design changes and or change of requirements. An example is the need for an AR-coating on a lens. At some point in time, a more sensitive sensor can make the need for AR obsolete, leaving a $5 million investment unused all of a sudden. The same example, but then reversed, can cause supply chain disruption: smaller pixels and need for (better) coatings can induce a change of supplier, to one which has the right equipment available.

Price pressure in other parts of the food chain also can cause radical technology changes, such as the above-mentioned choice for wafer level optics instead of molded plastic optics. The first being able to withstand reflow temperatures, the second not.

10.3. Observation 3: yield is king

Analysis on the costing of the plastic part shows that 50% of the price reduction must come from yield and uptime improvement. Other major cost parameters are related to the design are less easy to change. Without yield improvement profit goes down by 10% per year.

10.4. Observation 4: look twice – think three times

In large volume we have an explosive combination of large attractiveness from a business perspective and a large risk, due to the needed upfront investments, and explosives need to be handled carefully.

11. Conclusion

Only excellence on all aspects makes a winner. This is true in general for winners: they have an excellent performance. However, in the case of manufacturing optical components for mass consumer markets we have a situation more like driving a Formula 1 car: first of all every single contributing process in the chain needs to be executed in a near perfect way, and secondly a mistake can have dramatic consequences. However, when the job is done right, there is champagne.

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Rien de Schipper, MSc holds the position of General Manager of Penta HT Optics. After his study in Mechanical Engineering at the University of Technology in Eindhoven, he specialized in injection molding technologies with Philips Competence Center Plastics. As an expert for optical molding he took the lead in setting up development and manufacturing capabilities for CD-lenses in Philips High Tech Plastics since 1984 and for miniature camera optics in 2000. Currently one of his main fields of attention is to guide users of optical parts and assemblies towards optimal solutions in terms of cost and fit for use.