EN ROUTE TO VOLUME PRODUCTION OF CPV OPTICS

Thomas Luce¹ and Joel Cohen¹
¹Eschenbach Optik GmbH, Nuremberg, Germany

ABSTRACT

Most important for the commercial success of large-scale CPV power plants is the ability to cope with the enormous production demand. The challenge is to produce multimillion parts per year and to achieve at the same time high quality parts at low price. Therefore the manufacturing processes have to be well chosen. They have to be reliable, stable and capable of high volume output. Only this will guarantee the commercial success of CPV. For optical components such as primary and secondary optics mass production concepts with different cost potential exist - the most promising is injection molding. This manufacturing process technology for optical components is already approved in mature industries like Automotive and Semiconductor. While the capability of injection molding of optical components for mass production is already well established in these industries, it needs to be proven that the high quality requirements in CPV can be met as well.

A variant of the classical injection molding process is injection compression molding. Its advantages are the lower cycle times, resulting in lower cost, and higher achievable quality (e.g. lower tip radii, lower inner stress). For efficient mass production the injection molding process can be fully automated by using commercially available standard equipment.

INTRODUCTION

The basic idea of Concentrated Photovoltaics (CPV) concepts is the replacement of expensive PV chip surface by cheaper optical elements to reduce costs of electrically generated power. Various concepts for this idea exist. Many systems are using a one- or two-lens approach. One of the prerequisites for a concept to succeed is of course the cost e.g. for trackers and more efficient PV cells that are compensated by the savings due to the use of cheaper optical elements. During the starting phase of CPV the focus was on feasibility, now manufacturability and especially cost efficiency are keys for a fast market penetration of CPV systems. Both primary and secondary optics require mass manufacturing processes allowing scaling of the quantities up to several million parts per year, while keeping quality and cost at the lowest possible level.

A promising approach is to learn from industries where the transition from low to high volume production has already been accomplished. In the automotive lighting and semiconductor (LED) area, the problems with optical elements are quite similar; the target is to achieve high quality and quantity at the lowest possible cost and to meet lifetime requirements even under harsh environmental conditions. As the best suited production technology for optics injection molding is established. As soon as the process is set accordingly, the quality of injection molded lenses is outstanding - very good surface quality and extremely low tip radii. Eschenbach Optik, a leader in the field of high precision molded polymer optics, has developed large scale production technologies to answer the demands of these industries.

The main cost driver for injection molded parts is the cycle time. Due to the faster processing of the polymer by injection molding compared to hot embossing - the material is already molten in the injection unit - and the option to use multi-cavities, the part price drops significantly with larger quantities.

![Figure 1 Cost comparison: Parts made by injection molding compared to parts made by hot embossing ([1], for single cavity molds). The graph suggests that the price potential for injection molding is much better than for hot embossing. For multi-cavity tools the cost for injection molding will be even lower.](image-url)

INJECTION MOLDING OF OPTICS

From a manufacturing point of view the large quantities of Fresnel lenses needed for CPV power-plants require a fully automated production process with short cycle times. While for prototypes and small series hot embossing is a good choice, for real mass production a process which can be automated more easily is needed. Injection molding has been proven to be capable of a mass production of optical parts in high quality. It uses standard production equipment and the cycle times are typically very short. A typical comparison showing the advantage of injection molding versus hot embossing is shown in Fig. 1.
Replication quality of injection molding

To quantify the achievable quality of injection molded Fresnel lenses, several investigations have been performed on microstructure replication. As sample geometry edge shaped structures of 50\(\mu\)m step size and 2\(\mu\)m tip radius were used (Fig.2 bottom).

![Figure 2: 50\(\mu\)m-groove structure on the measurement sample (bottom) and geometry of the diamond tool used for cutting these grooves (top).](image)

These structures were manufactured using diamond turning with mono crystalline natural diamond tool (Fig.2 top). The optical insert was then measured and its shape used as reference for comparison with the injection molded part.

To define a metric to rate the results the optimum, parameters for a flat plate without structure were recorded. Then the optical insert was mounted and first shots were done using the optimal parameters for the flat plate. The profile depth (peak-to-valley) was measured and used as metric for the quality of the replication. It turned out that it matched very well with the overall impression of the structure quality (e.g. tip radius, planarity of the shoulder).

As an example, Fig.4 shows results without optimization (i.e. using the parameters for a flat plate). The replication performance is reasonable; also some degradation with respect to the tool insert is visible. The PV-value is 11\% higher than the tool inserts’ value.

![Figure 3: Shape of the tool insert with Fresnel-like structures of 50\(\mu\)m depth and 2\(\mu\)m tip radius.](image)

An optimization procedure brings the PV-value down to 2\% difference. The tip radius is comparable to the tool insert. This is shown in Fig.5, where a tip radius of less than 3\(\mu\)m can be measured. As a conclusion from these investigations, it can be deduced that injection molding is capable of nearly 100\% replication of the tool inserts. Of course, this makes careful optimization and control of the process parameters necessary, requiring significant experience in injection molding of optical parts.

![Figure 4: Non-optimized replication results using standard injection parameters and standard material, using the optical insert of Fig.2. The tip has a radius of about 8\(\mu\)m, a degradation of the PV-value of about 11\% relatively to the optical insert.](image)

Injection compression molding can improve the results.
CPV FRESNEL LENSES

Besides approaches using mirrors as primary optics, the most popular option for CPV primary optics are Fresnel lenses. The best suited thermoplastic material for this application is PMMA. It is a low-cost, high performance transparent material offering superior optical properties (high Abbe number, transmission rates (see Fig. 6)),

Figure 6: Transmission data of 3mm thick PMMA. For VIS and IR very good transmission data is achieved, in the visible area 92.03%. (Source: Evonik Industries)

good scratch resistance and excellent UV stability. PMMA is used since decades in many outdoor applications, e.g. roofs or car rear lamp lenses, so that a lot of experience is already available. PMMA fulfills the so-called Florida weathering test for automotive rear lamps. Using thicknesses of 3 to 4mm it also withstands the IEC 62108 hail tests mandatory for CPV systems. A further benefit from a production point of view is the easy processing of PMMA in an injection molding process.

A second approach would be silicone on glass (SoG). Due to the two components and the much more expensive base material, SoG Fresnel lenses are more expensive than injection molded PMMA Fresnel lenses.

PMMA Fresnel Lenses

In Fig.7 the result of the peak-to-valley (PV) deviation of an injection-molded PMMA lens is given. It shows a very good PV-deviation of the plane surface of about 5µm. Cycle times for such an injection molded lens can be as low as 1 minute.

Figure 7: The peak-to-valley deviation of the Fresnel structure for injection molded PMMA-lens is 5µm!

Figure 8: Microscopic section of the Fresnel structures of an injection molded Fresnel lens. Typical radii are about 2 µm and are varying only slightly over the whole lens.

The replication of Fresnel structures is very good. Radii of the Fresnel tips are in the order of 2µm and have been achieved with a 2µm radius on the tool. Thus, the replication quality is very good with only slight deterioration of the tip sharpness of the tool.

Optical Efficiency

For CPV application, the optical efficiency is an important parameter. Results for injection molded parts from a galvanic insert with 2µm radius (1), a NiP-coated insert with 2µm tip radius (2) and from a prototype part (turned with a 2µm tip diamond tool) (3) are displayed in Table 1.

The data clearly shows that injection molded parts can achieve an efficiency of 85% (surface weighted) which means a reduction of only 2% under serial production conditions compared to a directly turned part.
Table 1: Comparison of the transmission efficiency of Fresnel lenses produced with optical inserts of different materials. Best results are achieved with a directly turned PMMA prototype lens (3), but an injection molded sample with NiP-coated optical insert with 2\(\mu\)m tip radius (2) gives an efficiency of 85%. The lens produced with a galvanic insert (1) reaches only 82%.

A further quality aspect is the nonexistence of inner stress which weakens the parts mechanically and may result in early fatigue. Inner stress is visible under inspection with polarized light.

Fig. 9 shows a qualitative birefringence measurement of an injection molded Fresnel lens. As it can be seen, the lens shows only little stress in the injection gate area (top of the picture).

Another option to reduce the stress even more is to use injection compression. While the tool itself is more complex due to additional mechanics for the compression stroke it removes nearly completely stress which results in a part with a homogeneous polarization image.

SECONDARY OPTICS

Secondary optics made from silicone serve to optimize and homogenize light focused by Fresnel lenses onto solar cells. This leads to an increase of the overall system efficiency even under poor light incidence conditions.

Because of the high energy densities and concentration factors in CPV applications, conventional thermoplastic materials such as PMMA and PC cannot be used for secondary solar optics.

Here, silicone is the ideal material as it is insensible to high energy densities and resistant to UV radiation and shows transmission rates of up to 95%.

Our silicone optics are manufactured with injection molding machines specifically adapted to silicone processing.

Multi cavity tools with up to 64 cavities for optical parts are feasible and are already existing, allowing the production of tens of millions of lenses per year from only one injection molding tool.

Fig. 10 shows a mass production lens with silicone optics, with 32 cavities.

Of course, due to the high number of cavities and using a fully automated process, very high part quantities at competitive prices are feasible.

Special care needs to be taken for the fixation of the optics on the chip. A mechanical solution is often possible, e.g. using the elasticity of silicone.
Most common is the use of an index matched silicone glue, which allows an off shore production of the optics at the lens manufacturer site and an assembly on the production line of the CPV manufacturer. Another option can be the in-line overmolding of the lens directly onto the chip. Although this is feasible in principle by inserting the PCB into the mold, the PCB design has to be adapted to withstand the heat and mechanical stress during the injection molding process. Especially wire bonds need to be protected, and circuit paths have to be placed in a way to allow the correct tightening of the cavity and not to be damaged during the process. Also the closing of the mold has to be very accurate to prevent silicone from draining which results in flashes and pollution of the board surface. Once these challenges are solved, the overmolding process is very efficient.

Figure 11: Examples of secondary optics prototypes from transparent silicone. These parts are made from a prototype mold, showing the design freedom available for this material.

OUTLOOK

From the experience in manufacturing high precision optical parts for mass markets the most suitable process for high volume and cost efficient production is injection molding. Fully automated and into the production concept integrated processes are key for achieving low cost and high quality optical elements. Here injection molding is ahead of other replication technologies. To further improve part quality and at the same time reducing cycle times an additional option can be a dynamic temperature control of the cavity. This results in better replication of small structures (e.g. Fresnel tip radius) by heating and cooling close to the mold cavity in function of the cycle.

Injected PMMA is an excellent candidate to fulfill all technical requirements for a high quality CPV primary optics application. For secondary optics the process development of inserting and overmolding PV cell PCBs with transparent silicone will result in significant cost advantages due to elimination of handling and gluing process steps.

SUMMARY

CPV is a technology requiring mass production means and processes. Therefore a close look at already well developed mass markets like semiconductor (LED) and Automotive shows that injection molding is the most suited manufacturing technology to satisfy the needs of this growing industry. Experiences acquired in the above mentioned sectors should be transferred to the CPV optical component production, to achieve best quality per cost ratio.

For primary optics, injection molding of thermoplastic PMMA Fresnel lenses are feasible and can be manufactured in very high quantities with superior quality. Also for secondary optics injection molding can be used, utilizing transparent silicone with its superior UV and temperature stability.

Not only high quality optics with very tight tolerances are possible but also the integration of mechanical elements for fixation and positioning can be realized easily on the part. This reduces furthermore the cost and improves the overall performance of the CPV system.

REFERENCES
