Prism peak rounding in injection molded Fresnel lens solar concentrators

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ABSTRACT

The construction of viable solar energy conversion facilities is dominantly driven by economic forces requiring the minimization of cost per unit of electrical energy (e.g. dollars per Watt). As such, high volume injection molded Fresnel lenses are a contending technology in concentrated photovoltaic (CPV) systems.

Injection molding of Fresnel lenses for CPV systems requires particularly sophisticated technology and process control. Innumerable factors affect the quality. One important metric which has a direct impact on concentrator performance and must be controlled in the molding environment is prism facet fidelity. For maximum performance, the tips of the peaks in the finished component should be as sharp as possible. When prism peaks are not perfectly sharp, this is called “peak rounding” and the metric for this is the “peak radius”.

The effect of peak rounding on the performance of Fresnel lens solar concentrators is investigated. A reasonable analytical model is presented. Also, this paper will review the process and production optimization on the inherent PVT (pressure, volume, temperature) relationship of the polymer that must be obeyed in the molding process. Finally, manufacturing data is presented as an example of the excellent quality level that can be achieved in an advanced high volume injection molding process.

1. OPTICS

The details for parameterizing a Fresnel Lens on it’s f/# and peak radii are covered in Ref. [1]. For the purposes of solar concentration, we only consider Grooves-Facing-Short-Conjugate (GFSC) configuration (shown in the adjacent figure). The f/# is defined as the focal length divided by the Clear Aperture diameter of the Fresnel lens. To scale into real world values, use the f/# and a known focal conjugate distance to compute the necessary aperture size. The f/# can be related directly to a derived maximum optical concentration ratio. The optical concentration ratio for an ideal “no-loss” Fresnel lens and a model including surface reflection loss at select Fresnel lens peak rounding values are presented.

An engineering experiment was conducted which varied process parameters in order to investigate the characteristic geometry of peak rounding. Based on the dimensions of the prisms characterized and the peak rounding radii measured, an approximation was made to relate the prism rounding ratio (defined as the ratio of the peak radius to the prism pitch) to the prism aspect ratio (defined as the ratio of the prism peak-to-valley height to the prism pitch).
Under normal Reflexite process operating conditions, the peak radii were too small to measure utilizing available in-house test equipment (Keyence VHX-600 microscope with 1,000× objective). In order to investigate the effects of peak rounding, sub-optimal processing conditions were implemented (results summarized for Conditions 1-3 in adjacent figure). Data from the so-called “Condition-2” process yielded peak radii in the range of 3-5µm. Henceforth this data was used to approximate how peak radii vary with respect to Fresnel lens f/#. This is correlated back into the model to explore transmission efficiency and the results are reviewed.

2. MANUFACTURING

Compression molded Fresnel lenses are capable of excellent quality with minimal prism peak rounding (<0.5µm radius). Injection molding is a very economical method but does not readily achieve the same fidelity. The main goal of injection molding a high quality CPV Fresnel lens is to take the best of compression molding (fidelity), eliminate its limitations (long cycle time, high cost) and combine it with the best of injection molding (short cycle time, low cost) to arrive at a high quality, low cost CPV Fresnel lens.

Obtaining the ideal injection molded Fresnel lens requires three production steps to be accomplished correctly and efficiently:
1. Fill the mold cavity with molten polymer as needed for optimal fidelity without damaging the polymer chains.
2. Solidify and cool the polymer into a part while minimizing pressure gradients and obtaining the targeted shrinkage that was designed into the mold tooling for correct performance of the optic design.
3. Eject the lens from the mold, and handle the lens in a manner that is environmentally consistent and does not impart additional stress to the part.

All three steps are related to both optical performance and production cost.

Fundamentally, filling of the mold cavity to achieve optimal fidelity is a function of material viscosity, tooling geometry and the available time and pressure window in which the geometry must be filled before the polymer solidifies. This is all due to the fact that polymers are non-Newtonian fluids while in the melt state and that the flow of melt state thermoplastics in the injection molding process is driven by pressure that exceeds the melt’s resistance to flow.

During the injection cycle, molten polymer flows from areas of high pressure to areas of low pressure. This is where facet geometry comes in to play. The typical Fresnel lens will have a nominal wall thickness of 2 to 4 mm while the typical facet geometry near the peak is orders of magnitude smaller. Because flow through small gaps requires more pressure than flow through large gaps, the polymer will preferentially flow along the nominal wall of the cavity and will only flow in to the facets when sufficiently pressurized. This flow behavior defines the pressure portion of the time and pressure filling window for a given Fresnel lens cavity geometry.

The other portion of the filling window is time. There is a time component because the temperature of the melt is significantly higher than the temperature of the mold cavity. This temperature difference causes the non-Newtonian polymer chains to increase in viscosity as a function of time as their velocity decreases to near zero and as they cool. The viscosity increase in turn requires even higher pressure to promote flow in to the facet geometry. At some point the pressure required to promote flow in to the facet geometry exceeds the available pressure and the polymer chains freeze in position. If the facet geometry is not completely filled at this time it will never fill and the result is a rounded peak of a given radius based on the facet geometry and the process conditions.

Once the cavity geometry and facet peaks have been optimally filled during the injection stage of the molding process, it is time to solidify and cool the part. This step must be performed in the correct manner in order to avoid molded-in stress that can lead to birefringence and distortion. An understanding of the PVT behavior of polymers is important to obtain a
high quality injection molded CPV Fresnel lens since solidification and cooling of the part can be up to 90% of the overall molding cycle. In general, the goal during the cooling stage is to adequately pressurize the mold cavity to compensate for polymer shrinkage while minimizing temperature and pressure gradients that lead to stress inducing shrinkage gradients. If this is accomplished correctly the result is a lens of uniform low stress with minimal birefringence.

Once the lens has completed cooling in the mold, it must be removed or ejected in a manner that does not impart any additional permanent stress. In addition, the post-mold handling of lenses should be very consistent in order to maintain uniform and optimal quality. Acrylic Fresnel lenses will continue to cool for some time after they have been removed from the mold and then they will absorb moisture from the air until they stabilize to ambient conditions 24 to 48 hours later. It is at this point that final lens dimensions can be checked and optical performance can be assessed.

To understand the PVT relationship to Fresnel lens peak rounding, the aforementioned engineering experiment was conducted on a CPV Fresnel lens (~300mm in diameter, 3mm thick, 250-500µm pitch). It was decided to use mold temperature as a variable since it would have the most significant effect on polymer melt viscosity at the peaks of the prisms. A second variable in the experiment was that of facet included angle: 53° at 500µm pitch and 33° at 250µm pitch. The facets to be analyzed were located adjacent to each other in the Fresnel lens tooling so that they would experience similar PVT conditions during filling and cooling in each run of the experiment.

Three conditions were run in the experiment. Condition-1 was a typical Reflexite High Precision Molding (HPM) injection molding process that achieves minimal (sub-micron) peak rounding. For Condition-2, the mold temperature was decreased to a known point of reduced fidelity but still well above that which would be obtained in a typical injection molding process. For Condition-3, the mold temperature was decreased even further to provide a sample set with significantly less fidelity which would be most similar to that of a conventional injection molded Fresnel lens. All other process parameters remained consistent and no adjustments were made to compensate for the effects of the mold temperature change. Test results will be presented.

REFERENCES